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Noma

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(54) **MAGNETORESISTIVE ELEMENT**

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G11B 5/02	(2006.01)
G11B 5/33	(2006.01)
G11B 5/31	(2006.01)

(52) **U.S. Cl.**
CPC *G11B 5/314* (2013.01)

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USPC 360/324.11, 49, 324.12, 234.3, 313, 360/314
See application file for complete search history.

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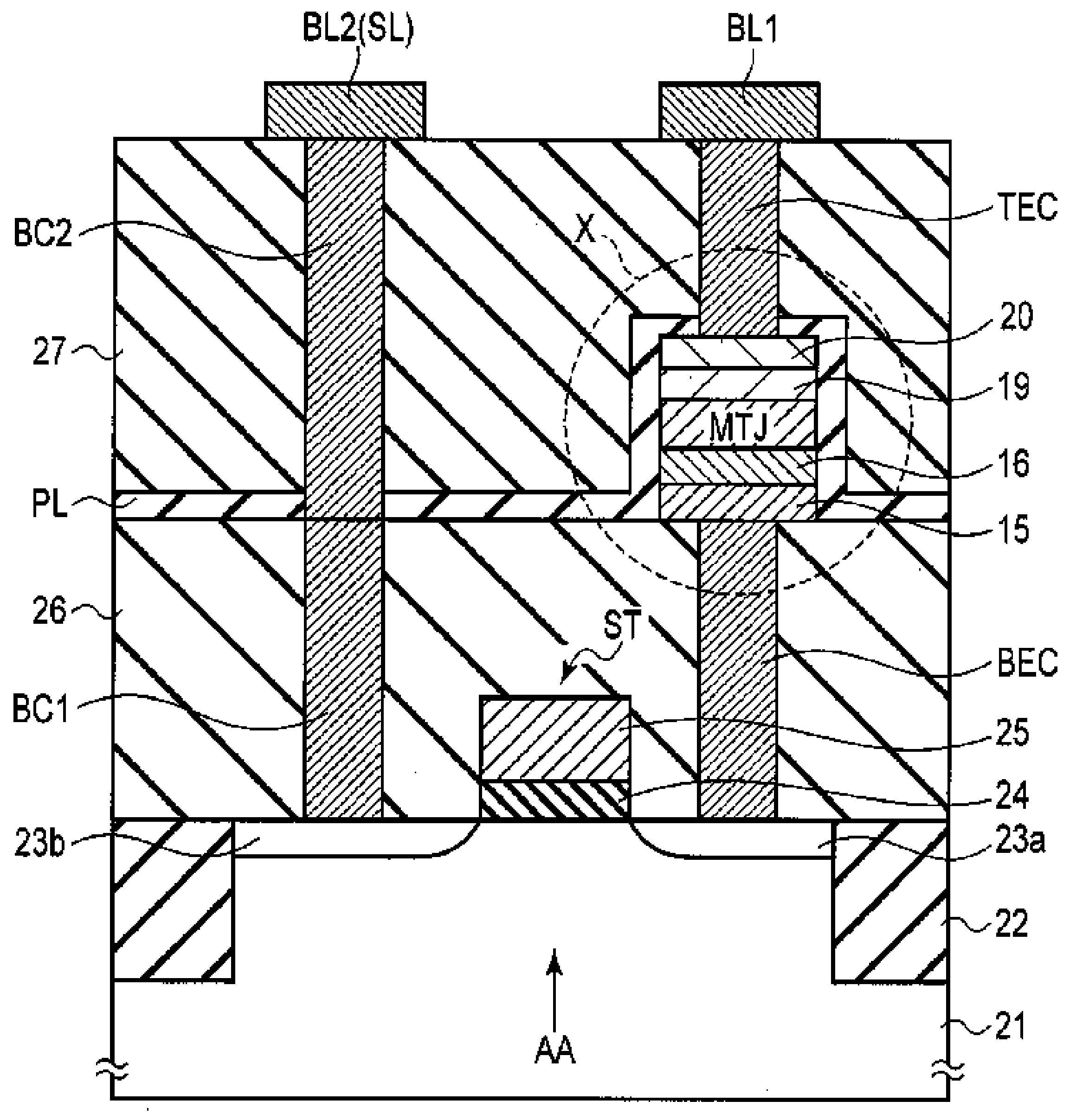
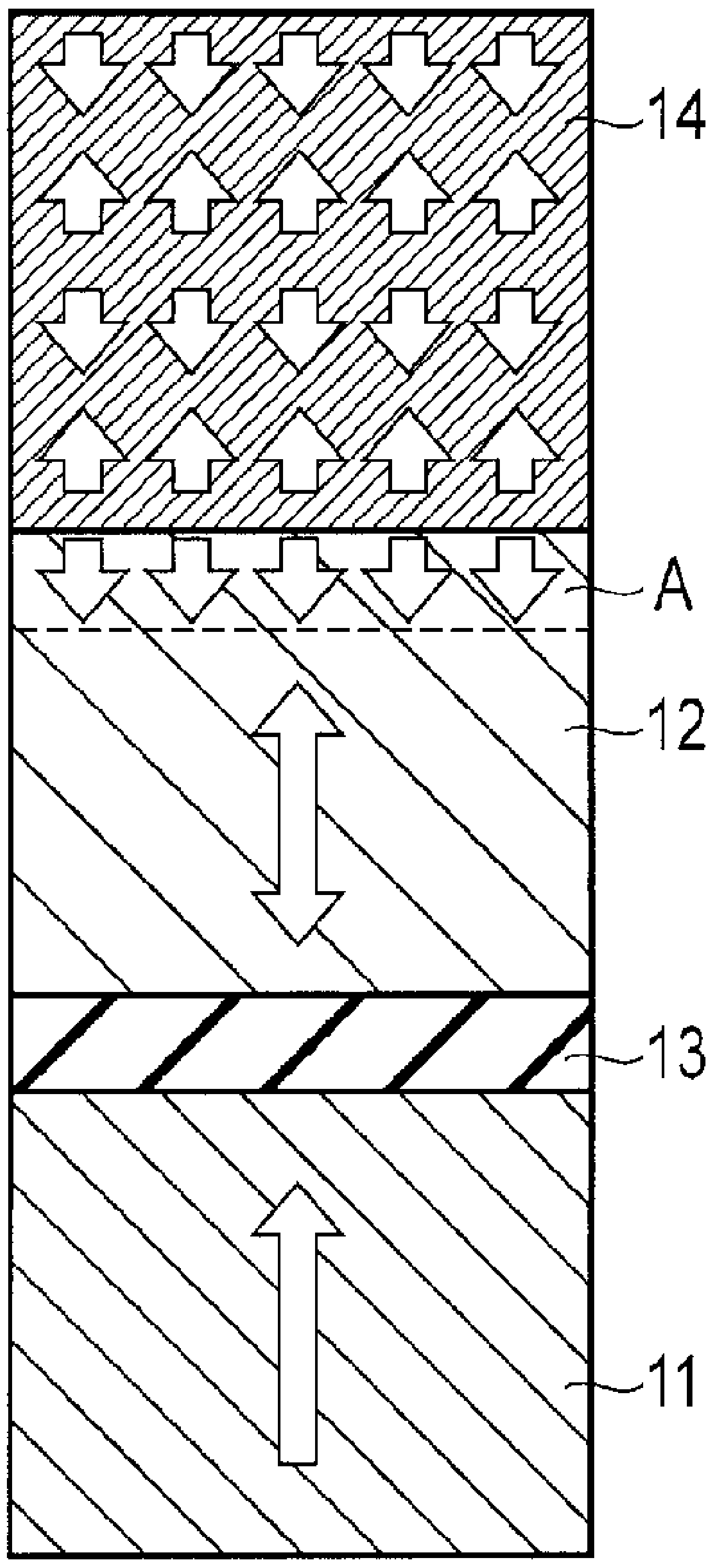
(74) *Attorney, Agent, or Firm* — Holtz, Holtz & Volek PC

(57) **ABSTRACT**

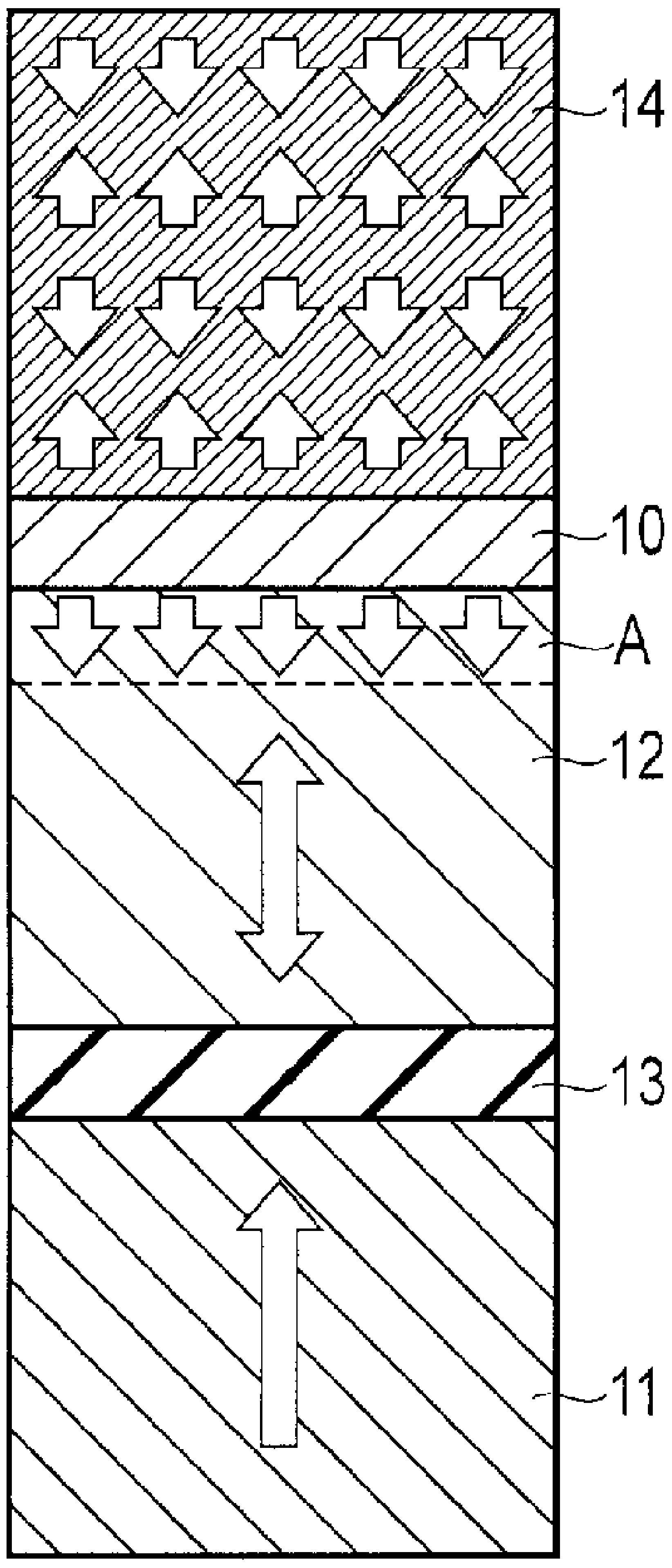
According to one embodiment, a magnetoresistive element includes a first magnetic layer as a reference layer, a second magnetic layer as a storage layer, a nonmagnetic insulating layer between the first and second magnetic layers, and an antiferromagnetic conductive layer which is adjacent to a side opposite to the nonmagnetic insulating layer side of the second magnetic layer in a vertical direction in which the first and second magnetic layers are stacked. The second magnetic layer includes an area which is magnetically coupled with the antiferromagnetic conductive layer and which has a magnetization direction parallel with a magnetization direction of the second magnetic layer.

18 Claims, 12 Drawing Sheets

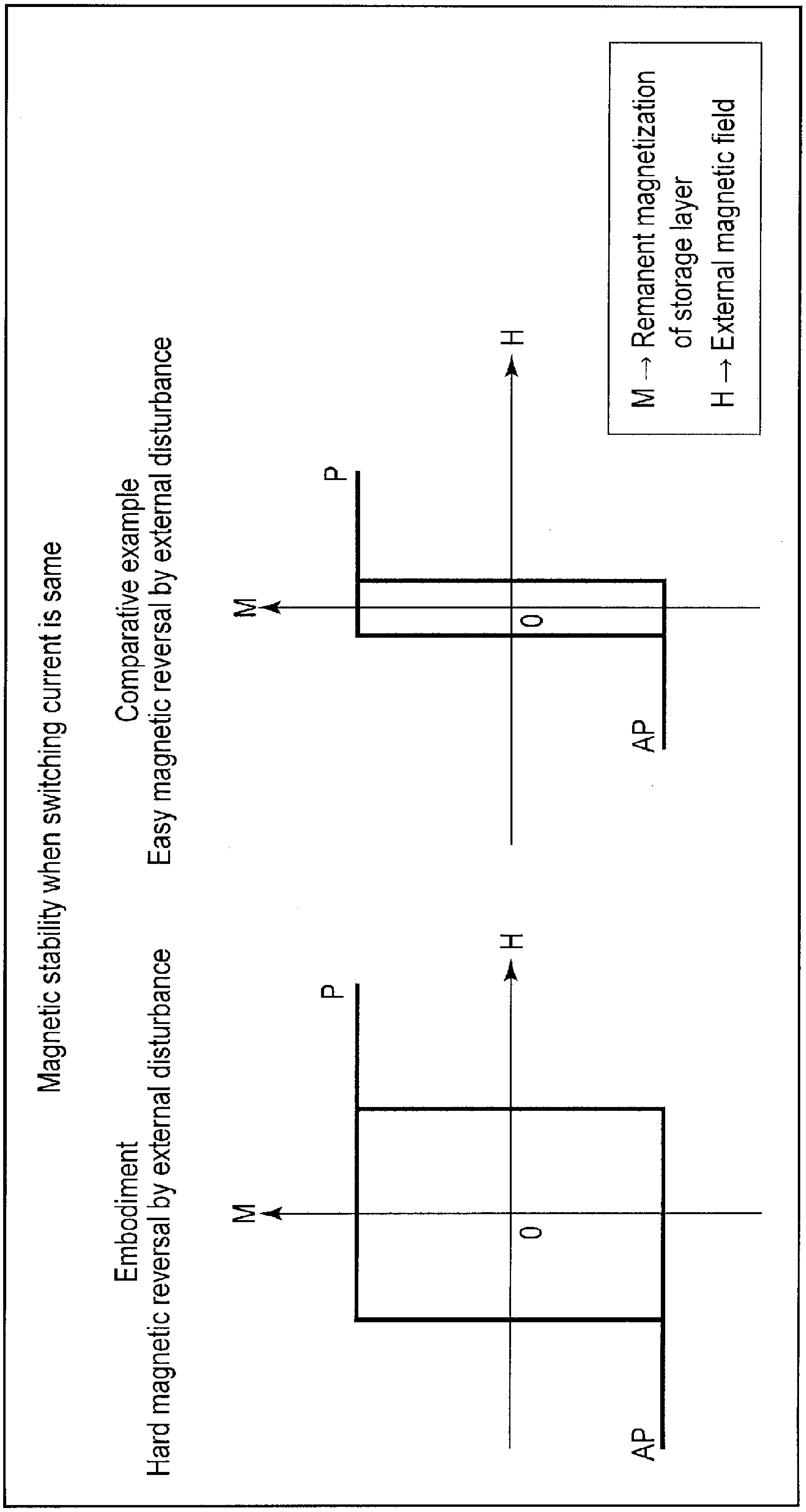




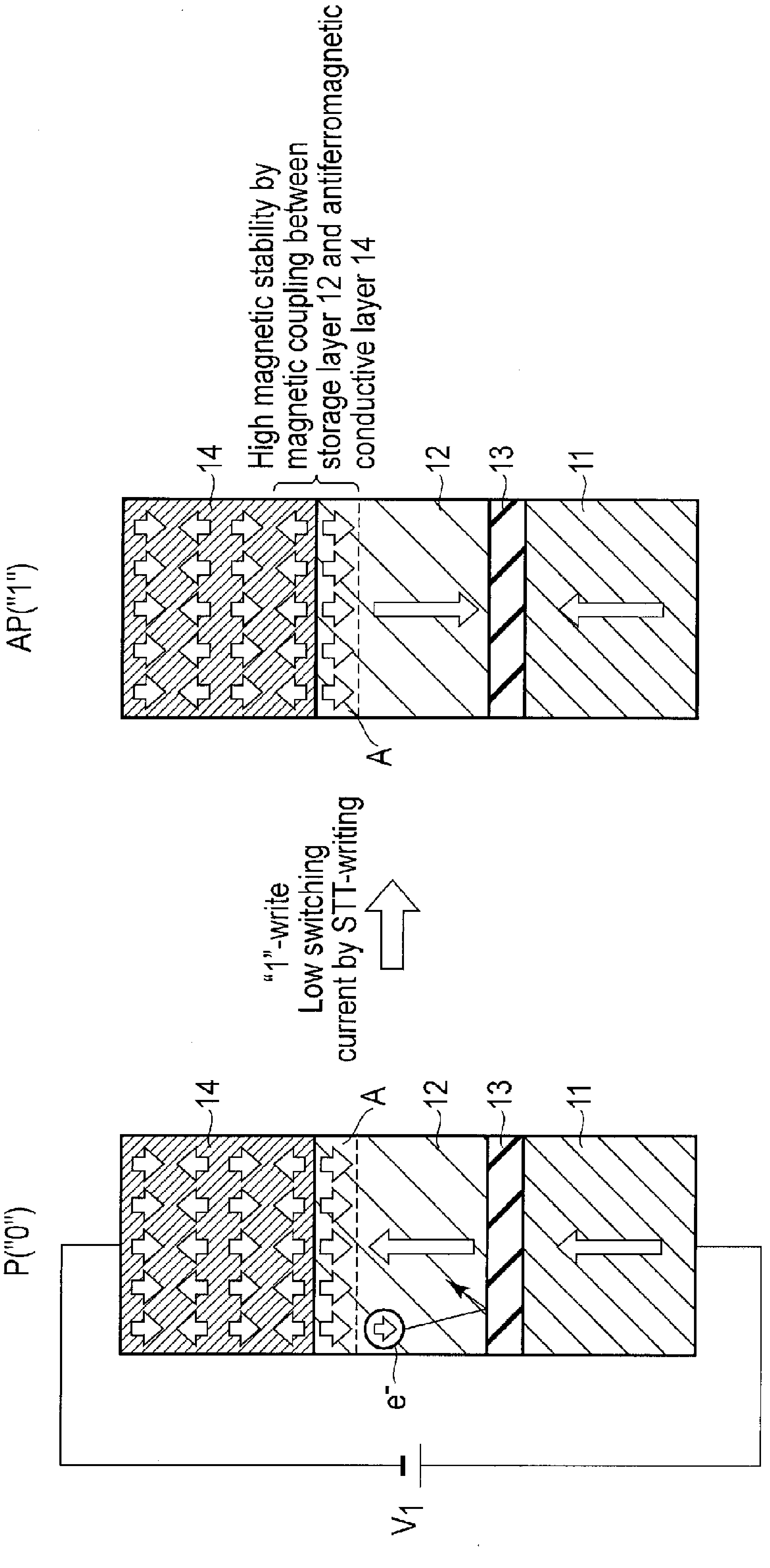
F I G. 1A



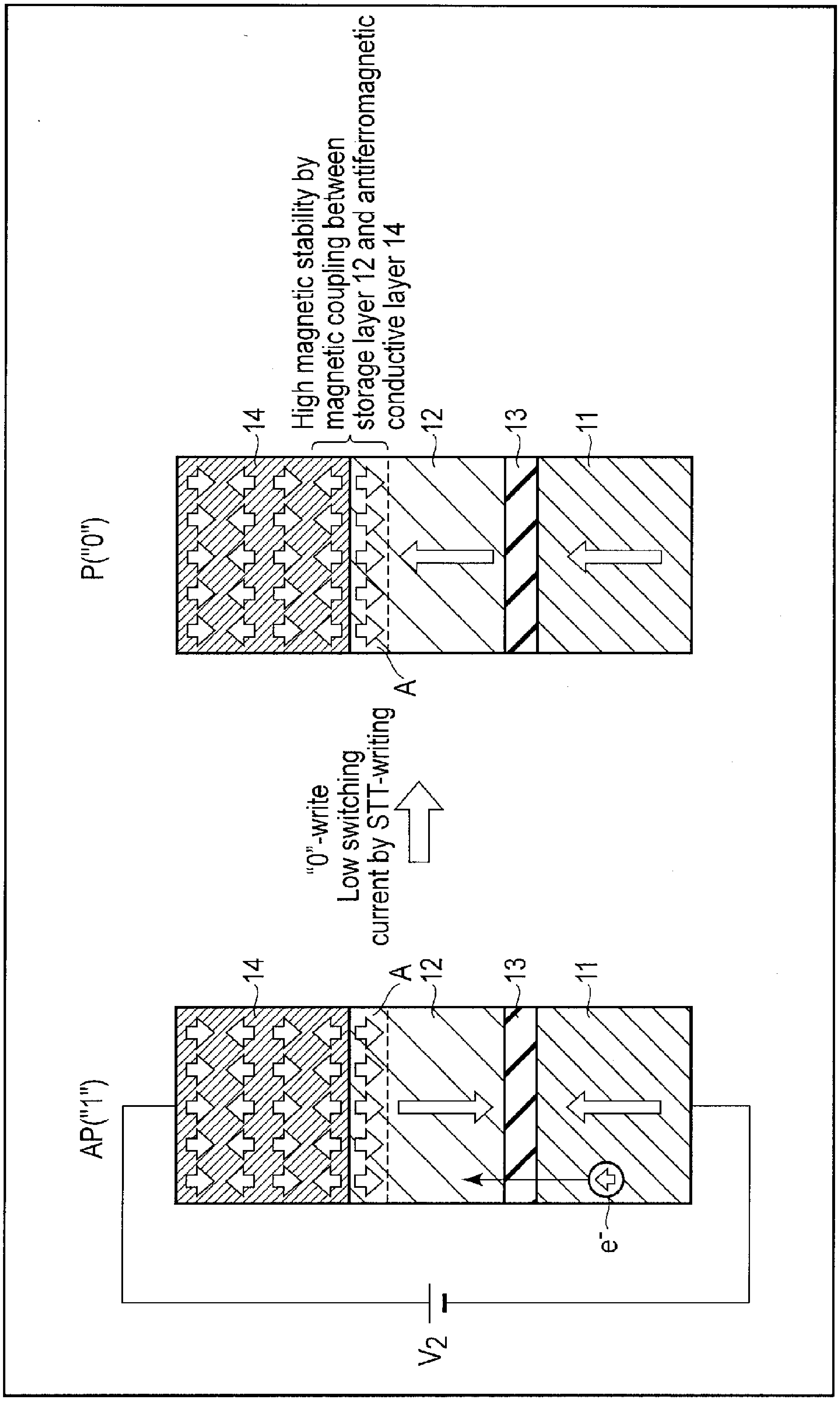
F I G. 1B


Magnetic stability when switching current is same
Embodiment
Hard magnetic reversal by external disturbance
M
H
P
0
AP
Comparative example
Easy magnetic reversal by external disturbance
M
H
P
0
AP
M → Remanent magnetization of storage layer
H → External magnetic field

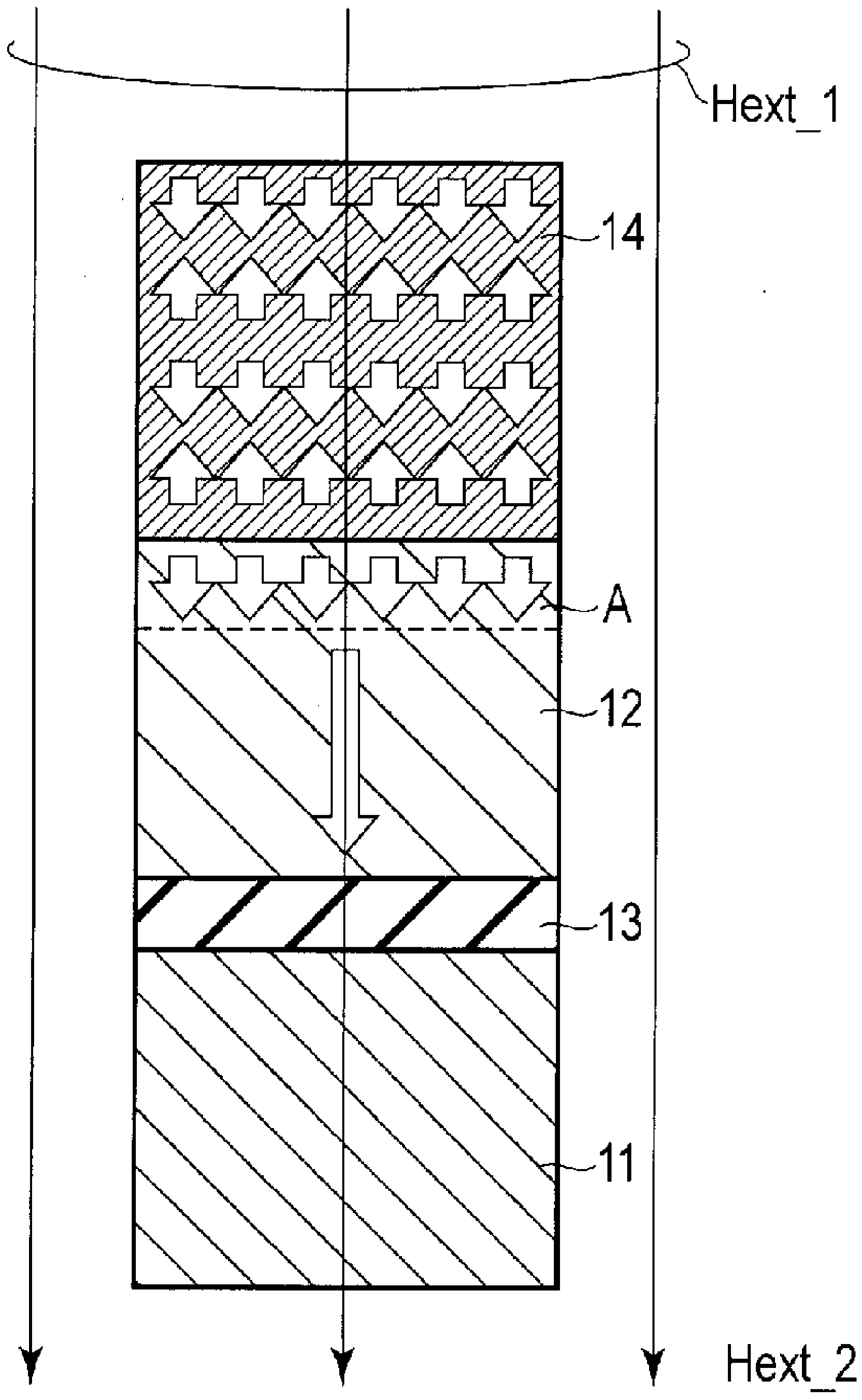
F I G. 2


P("0")
14
A
12
13
11
e⁻
V1
"1"-write
Low switching
current by STT-writing
AP("1")
14
A
12
13
11
High magnetic stability by
magnetic coupling between
storage layer 12 and antiferromagnetic
conductive layer 14

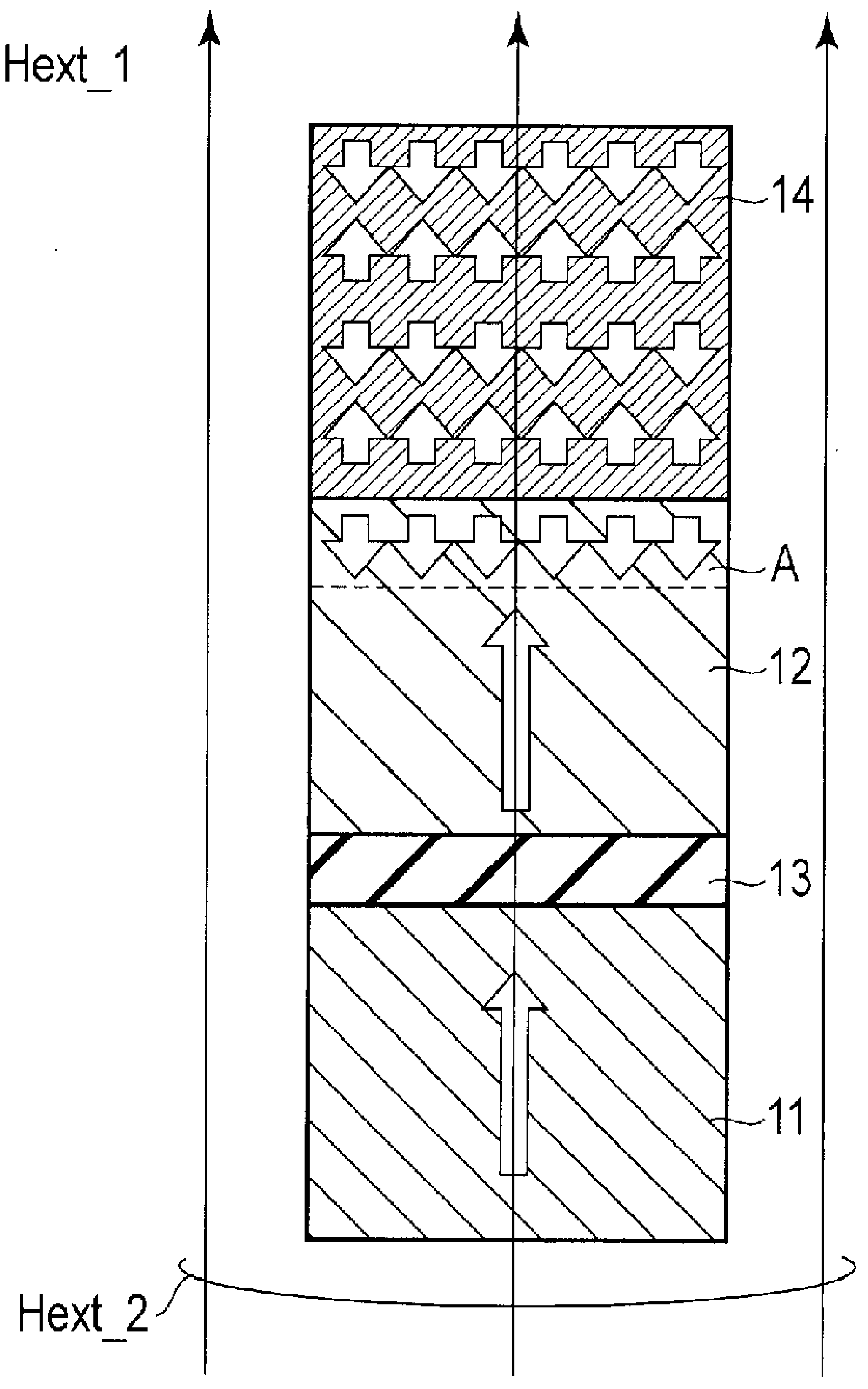
F I G. 3


AP("1")
14
A
12
13
11
e-
V2
"0"-write
Low switching
current by STT-writing
P("0")
14
High magnetic stability by
magnetic coupling between
storage layer 12 and antiferromagnetic
conductive layer 14
A
12
13
11

F I G. 4



F I G. 5A



F I G. 5B

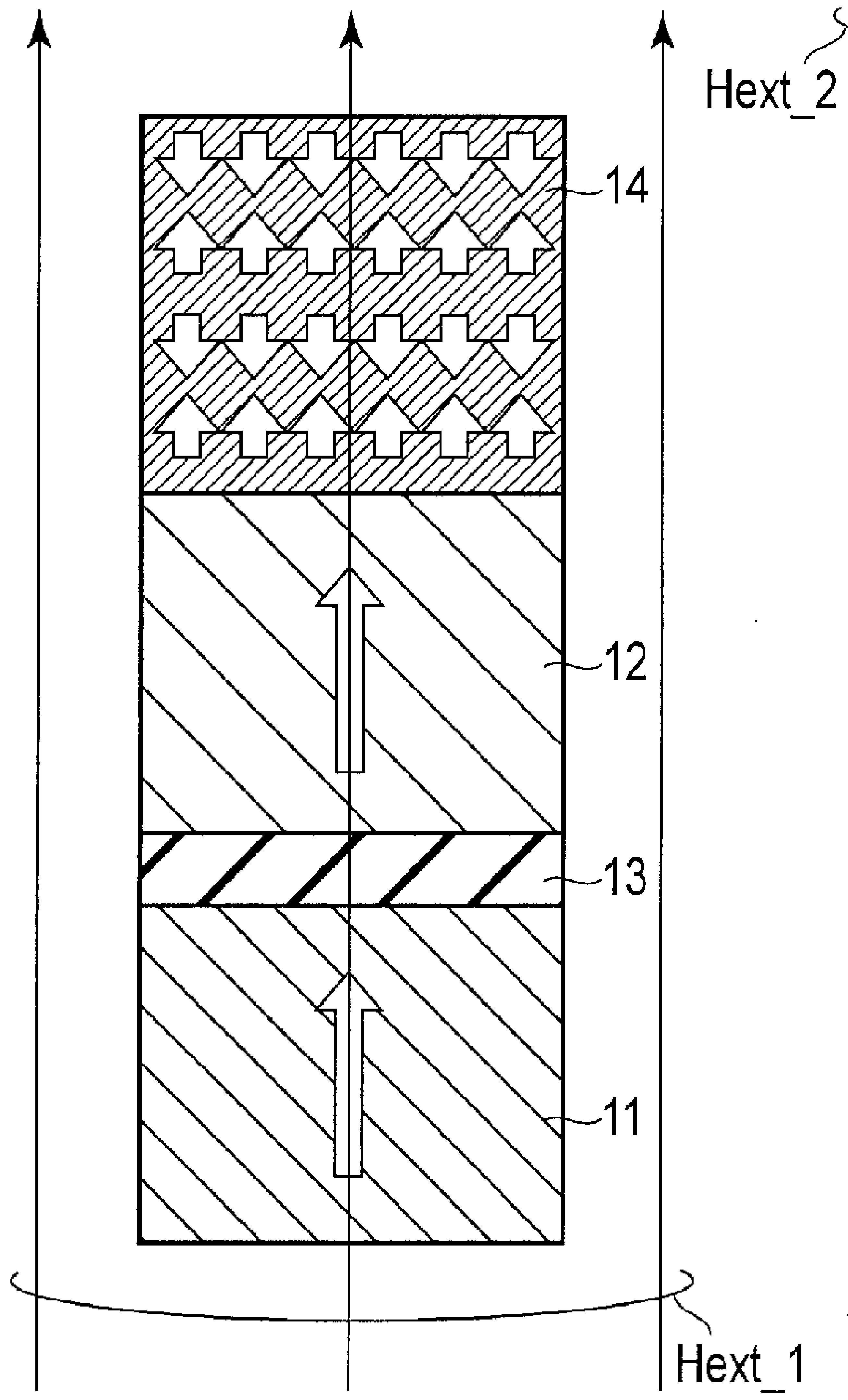


FIG. 6A

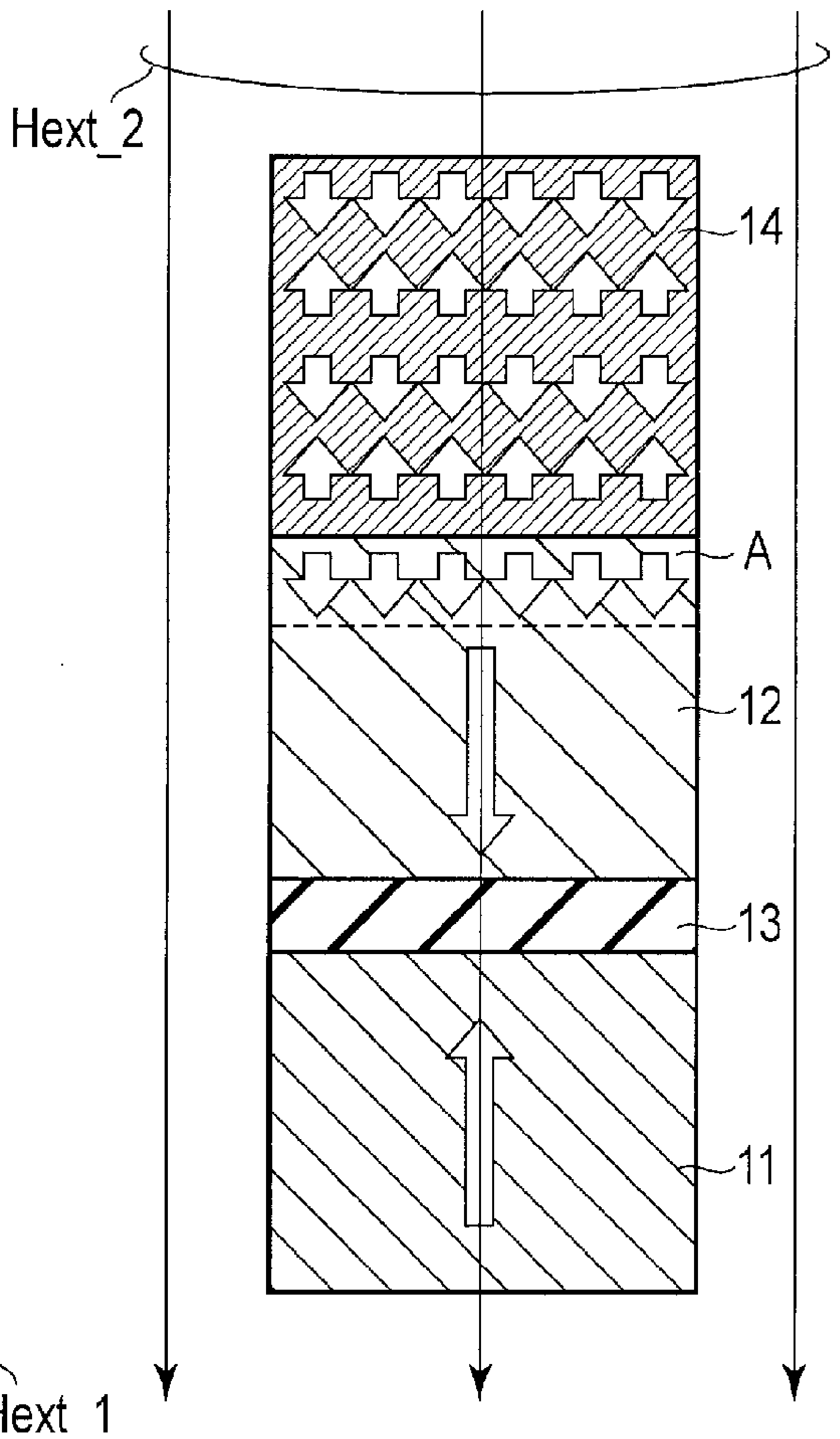
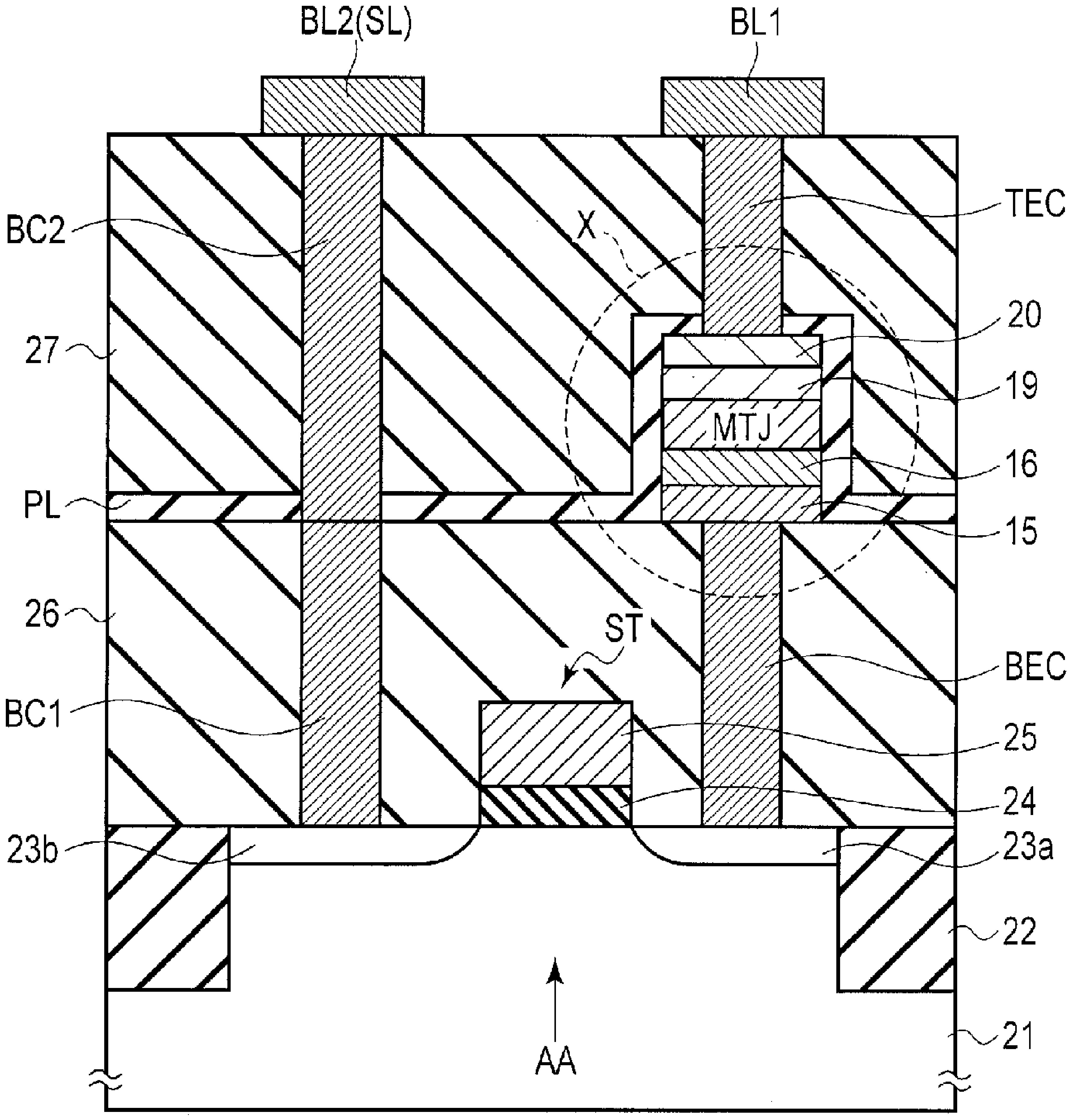
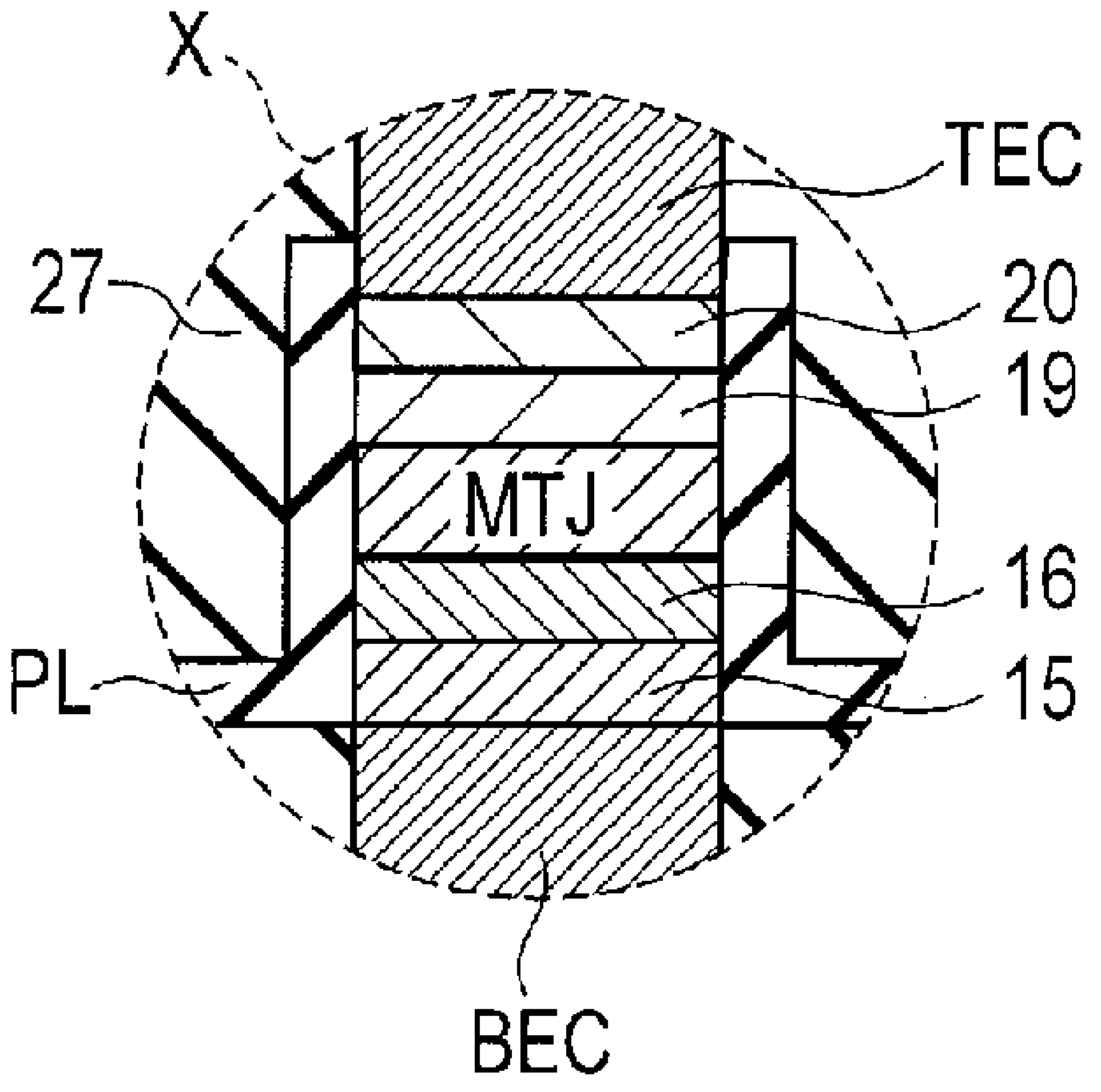


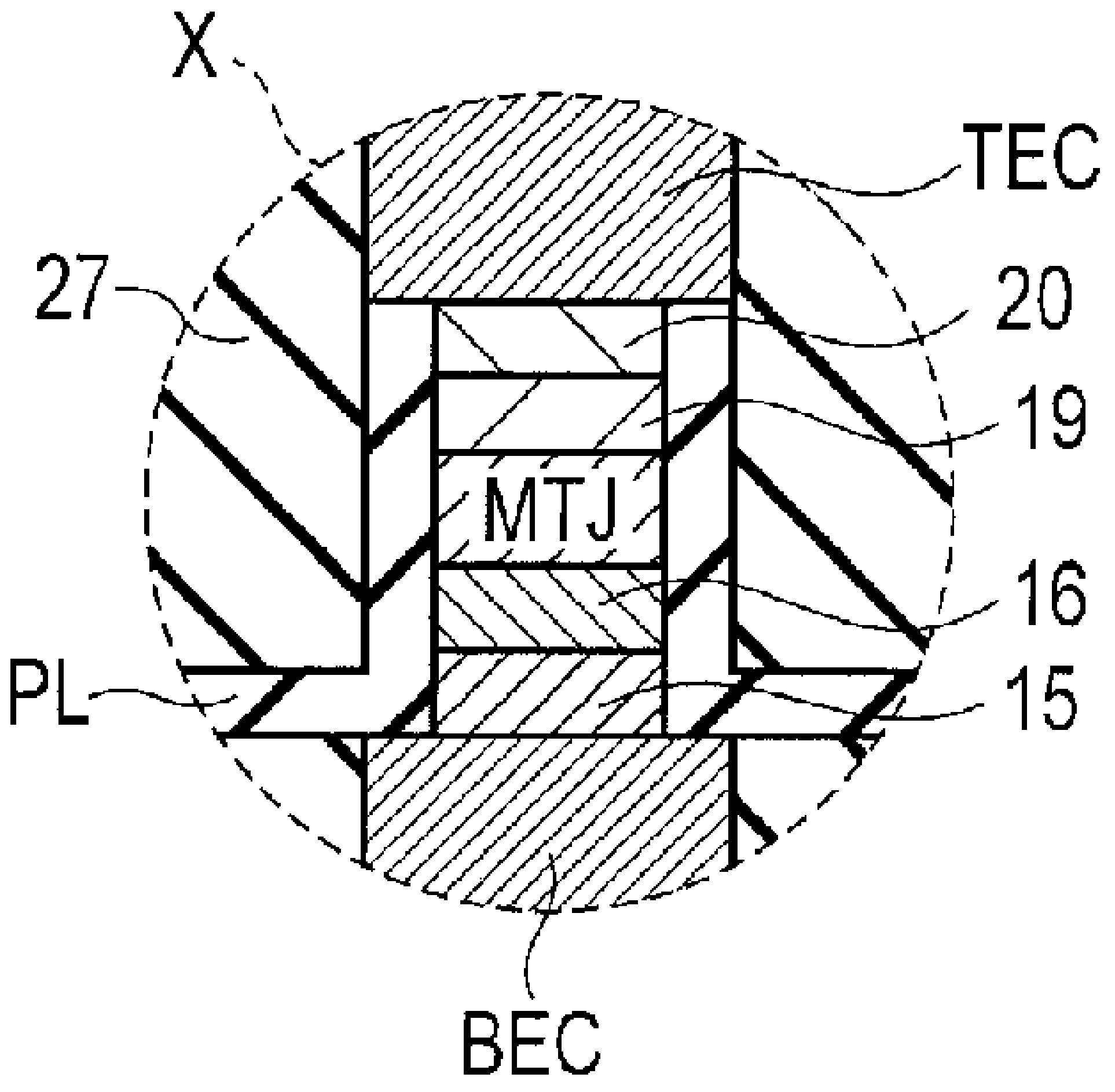
FIG. 6B



F I G. 7



F I G. 8



F I G. 9

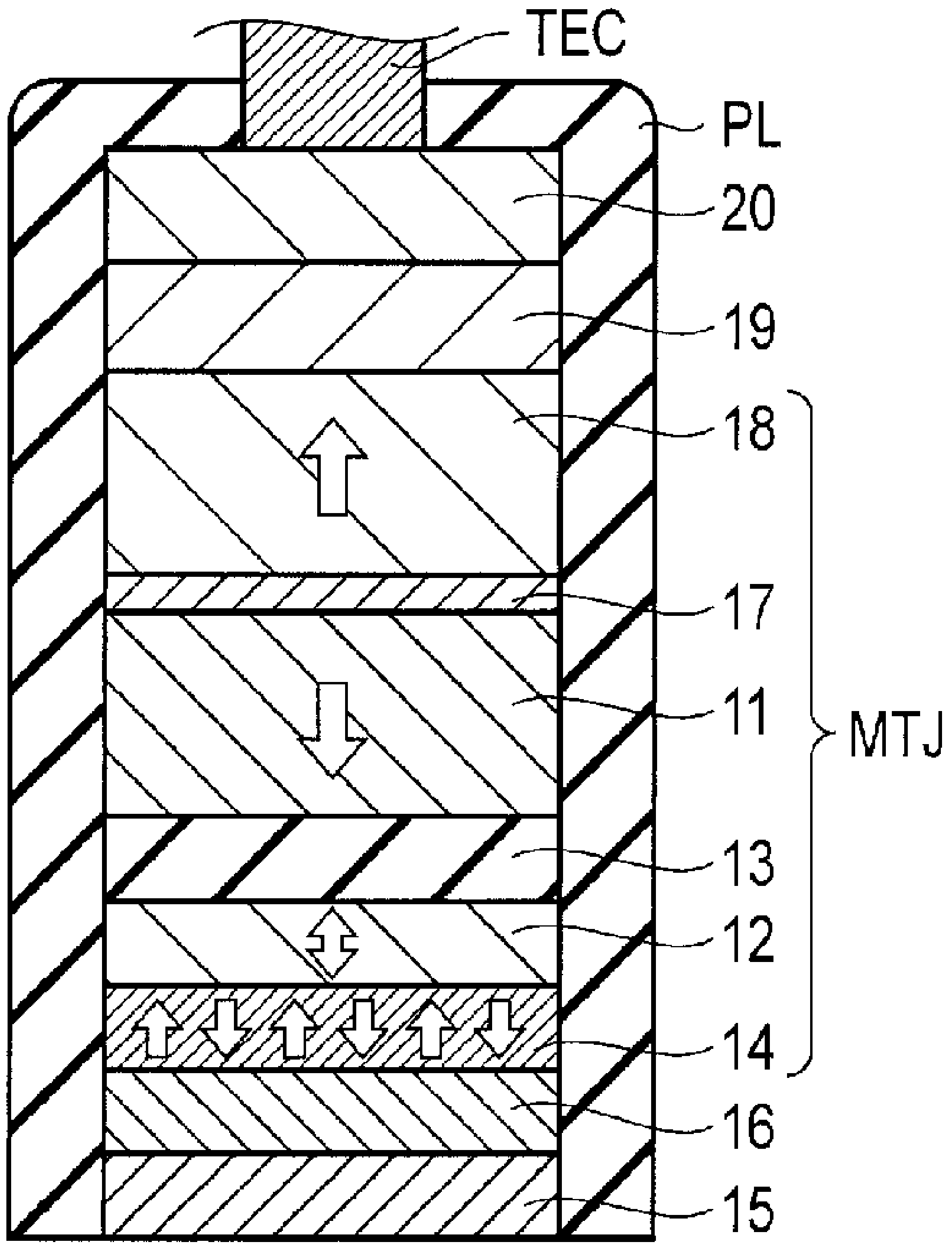

TEC
PL
20
19
18
17
11
MTJ
13
12
14
16
15

FIG. 10

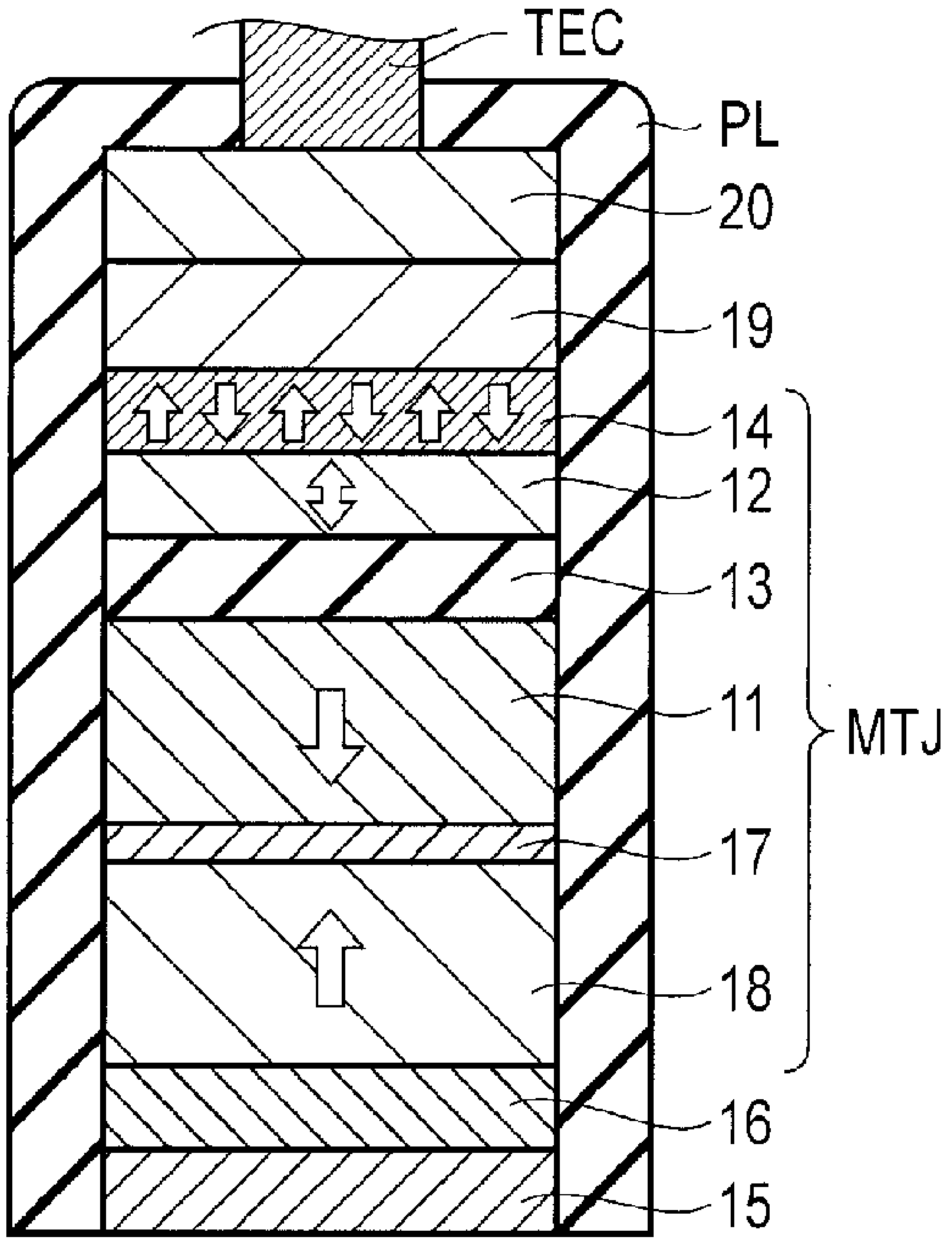
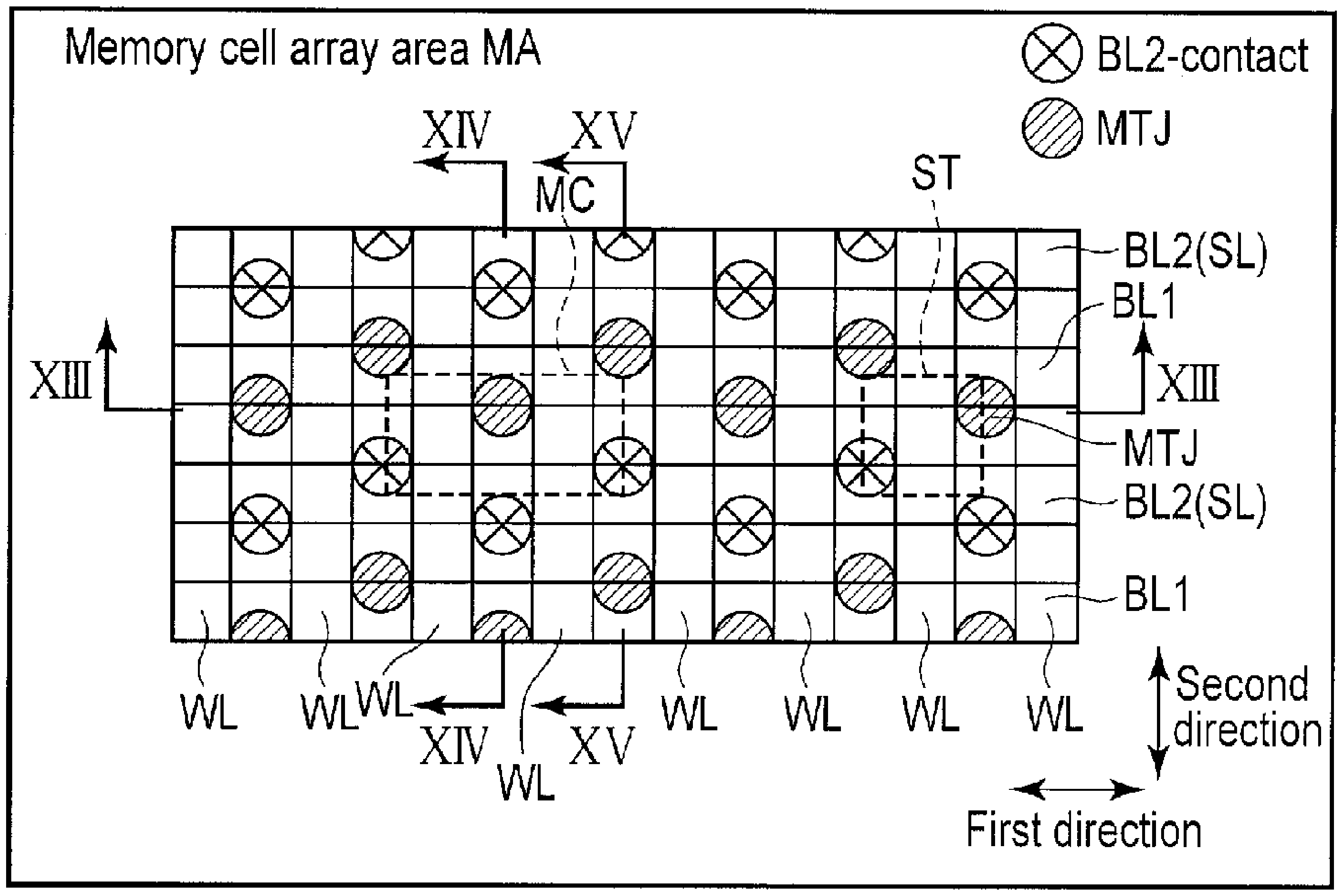
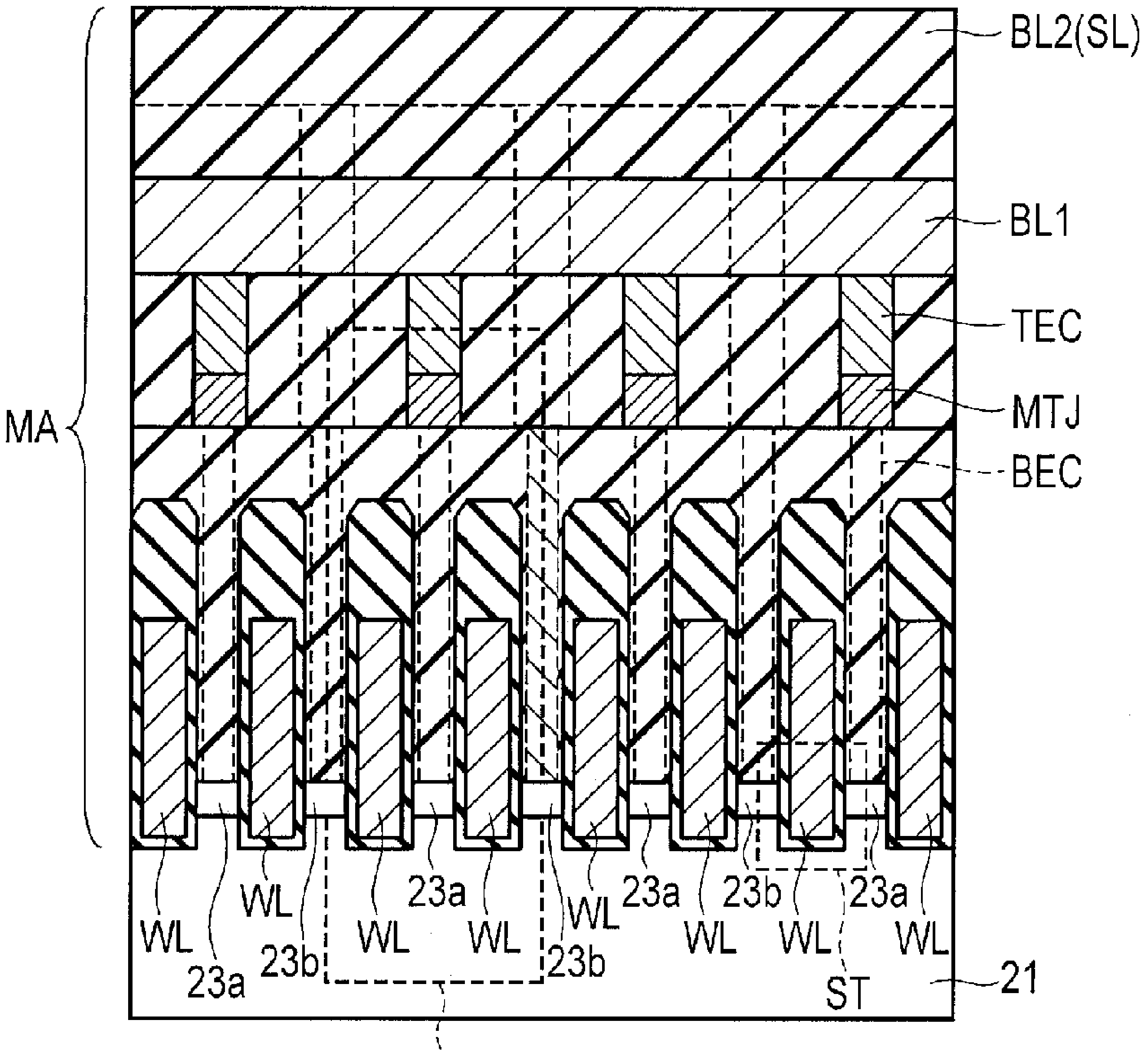

TEC
PL
20
19
14
12
13
11
MTJ
17
18
16
15

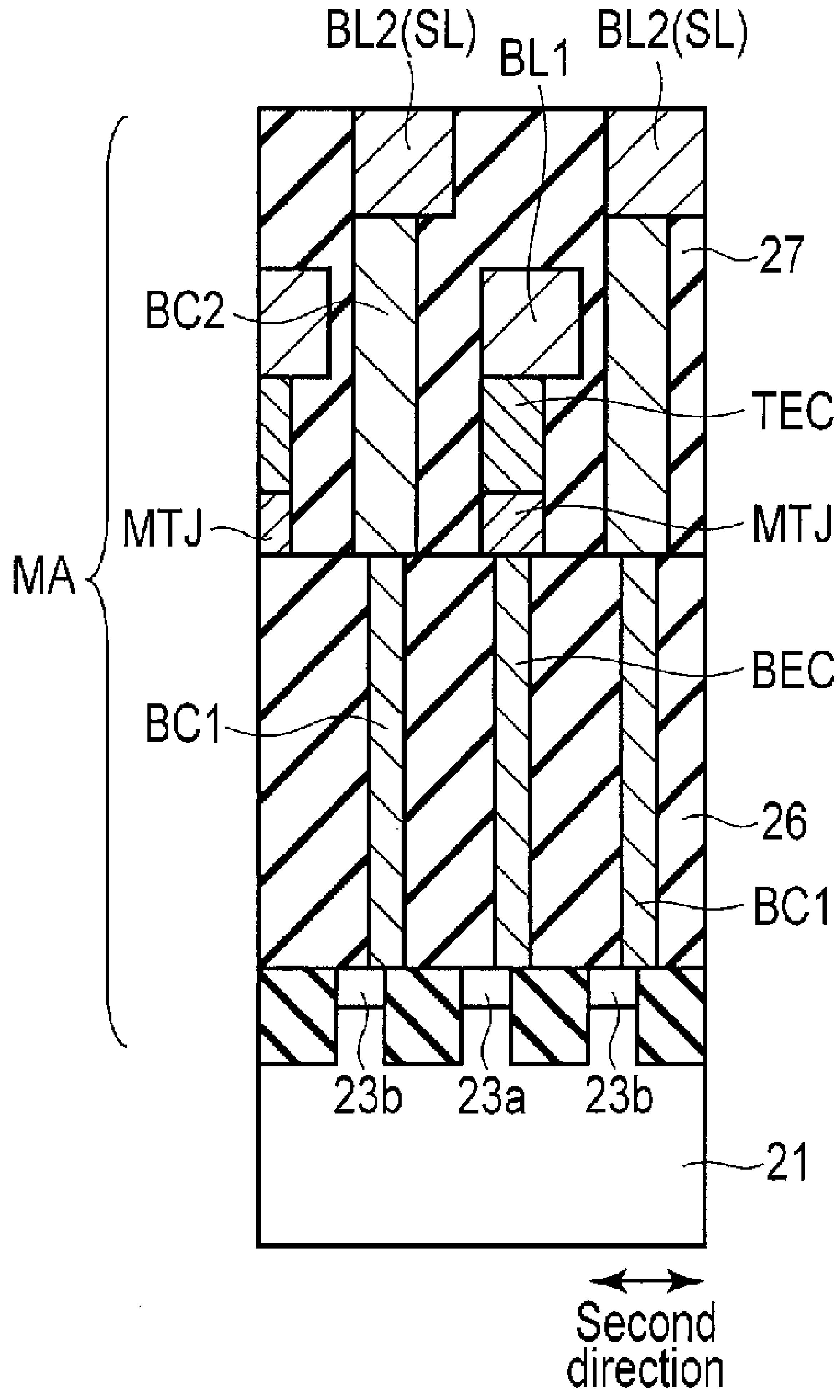
FIG. 11


Memory cell array area MA
⊗ BL2-contact
▨ MTJ
XIV
XV
MC
ST
BL2(SL)
BL1
XIII
XIII
MTJ
BL2(SL)
BL1
WL
WL
WL
XIV
WL
XV
WL
WL
WL
WL
Second direction
First direction

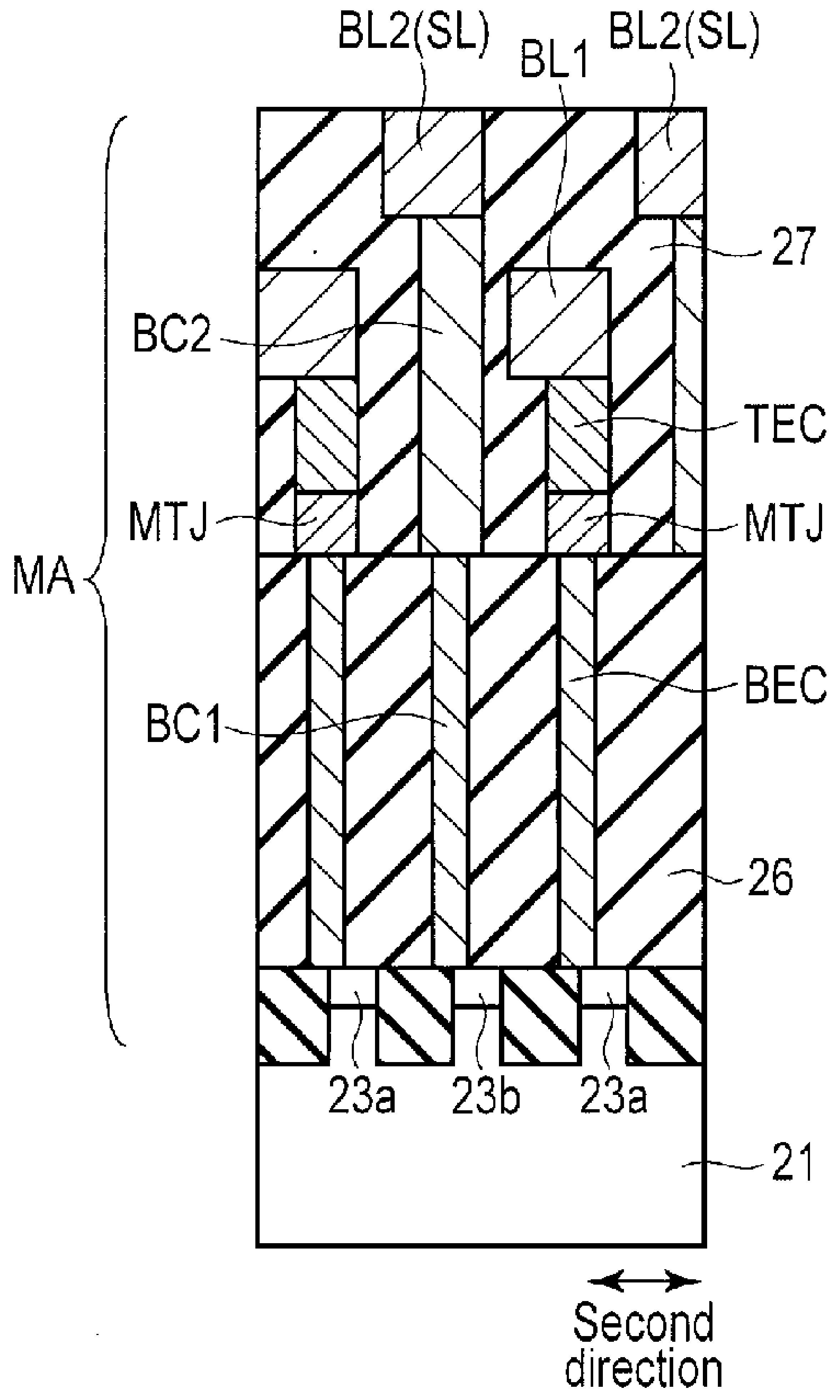
F I G. 12


BL2(SL)
BL1
TEC
MTJ
BEC
MA
WL
WL
23a
23b
WL
23a
WL
WL
23b
23a
WL
23b
WL
23a
WL
ST
21
MC
First direction

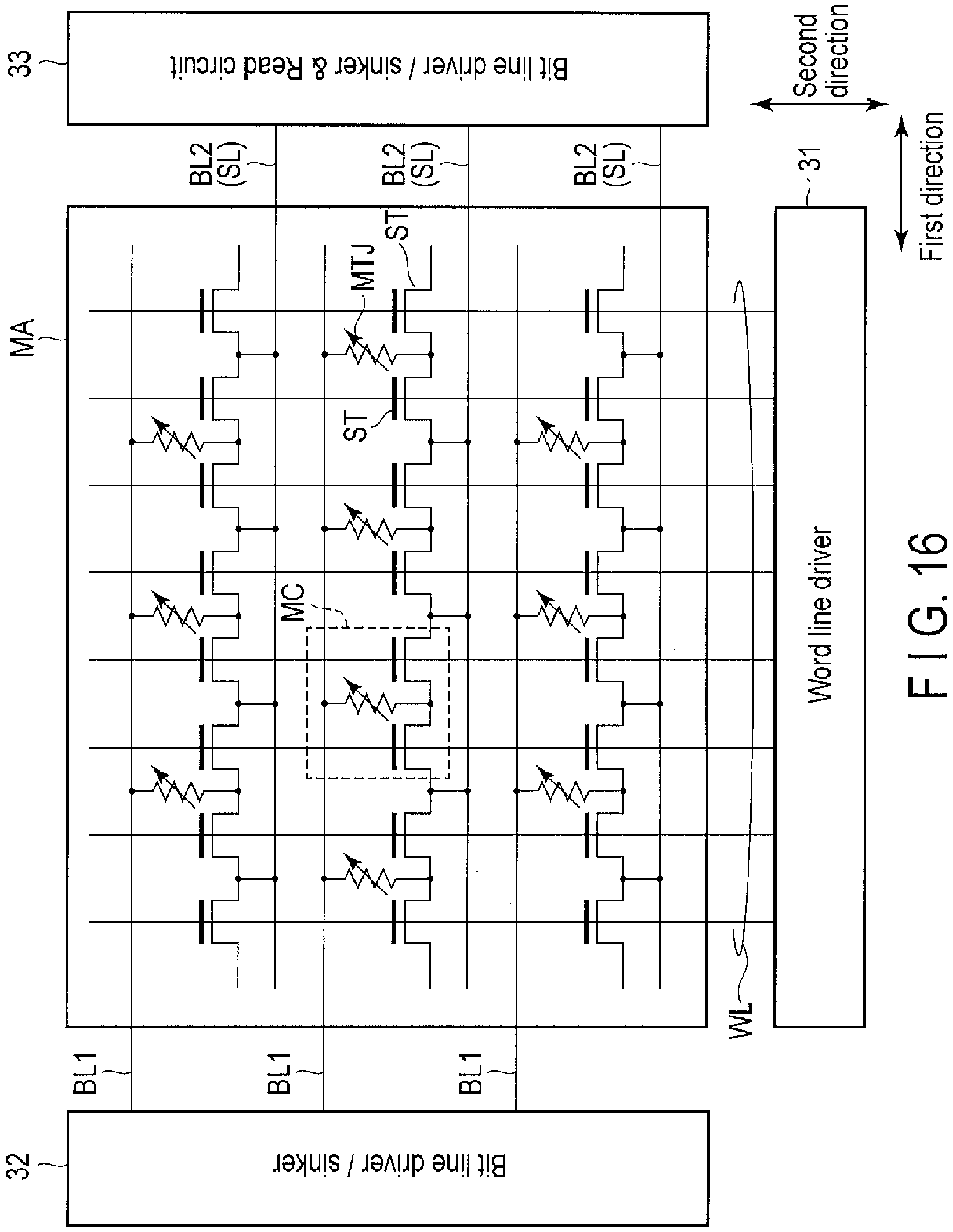
F I G. 13


BL2(SL)
BL1
BL2(SL)
27
BC2
TEC
MTJ
MTJ
MA
BEC
BC1
26
BC1
23b
23a
23b
21
Second direction

F I G. 14


BL2(SL)
BL1
BL2(SL)
27
BC2
TEC
MTJ
MTJ
MA
BEC
BC1
26
23a
23b
23a
21
Second direction

F I G. 15


33
Bit line driver / sinker & Read circuit
Second direction
First direction
BL2 (SL)
BL2 (SL)
BL2 (SL)
31
MA
ST
MTJ
ST
MC
Word line driver
WL
BL1
BL1
BL1
32
Bit line driver / sinker

F I G. 16

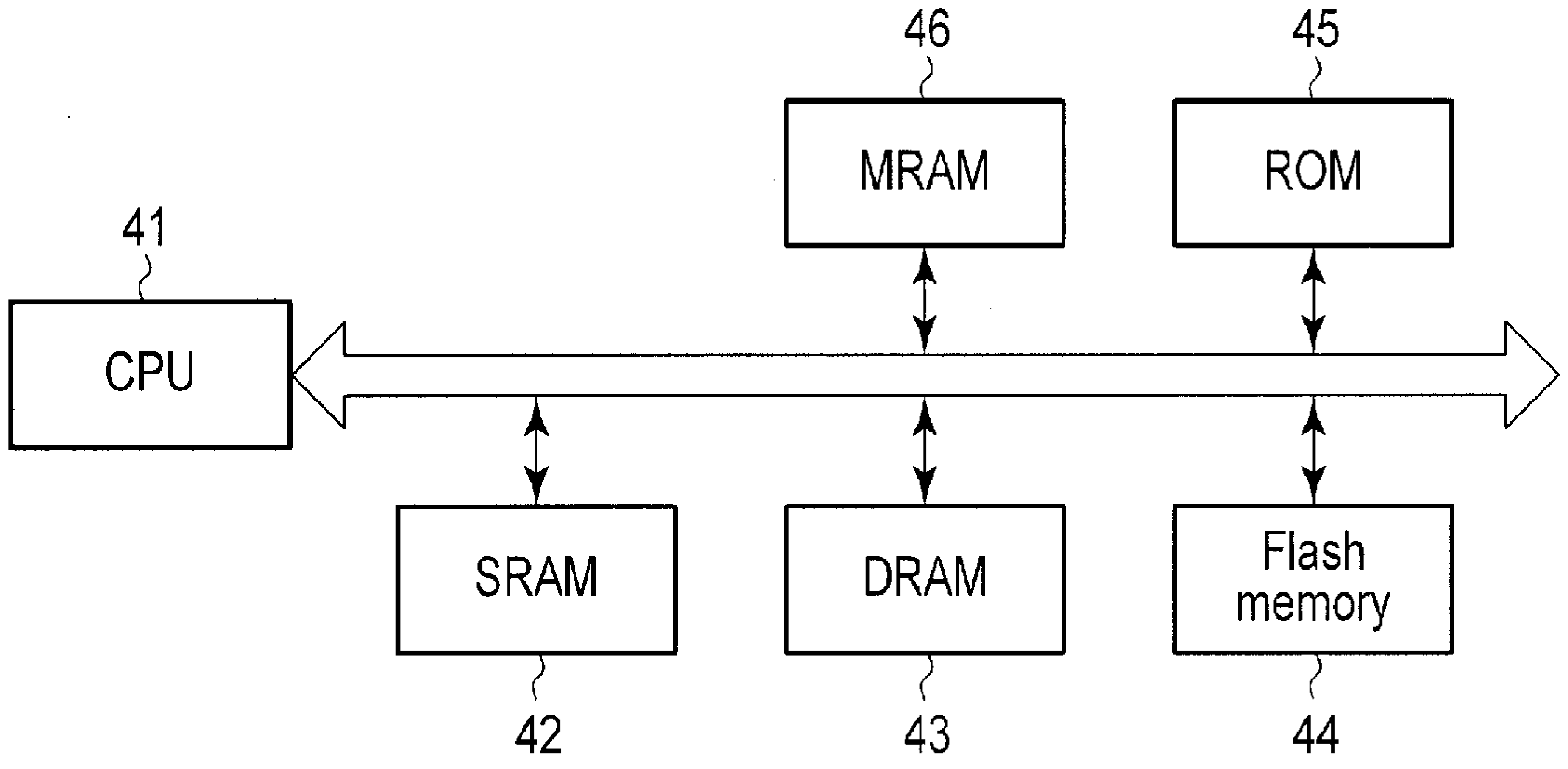


FIG. 17

MAGNETORESISTIVE ELEMENT

CROSS-REFERENCE TO RELATED APPLICATIONS

This application claims the benefit of U.S. Provisional Application No. 62/048,117, filed Sep. 9, 2014, the entire contents of which are incorporated herein by reference.

FIELD

Embodiments described herein relate generally to a magnetoresistive element.

BACKGROUND

The magnetoresistive element includes a reference layer having invariable magnetization, a storage layer having variable magnetization, and a nonmagnetic layer (a tunnel barrier layer) provided therebetween as its basic structure. When the reference layer and the storage layer have the same magnetization direction, the magnetoresistive element will be in a low-resistance state (i.e., a parallel state), and this state is referred to as, for example, the "0"-write state. Further, when the reference layer and the storage layer have different magnetization directions, the magnetoresistive element will be in a high-resistance state (i.e., an antiparallel state), and this state is referred to as, for example, the "1"-write state.

A write operation to bring the magnetoresistive element to the parallel state or the antiparallel state is performed by passing a write current (a spin injection current) to the magnetoresistive element, when, for example, spin-transfer torque (STT) writing is adopted. Here, from the standpoint of using less current, a value of the write current necessary for magnetic reversal of the storage layer should preferably be as small as possible. However, this means that the magnetic reversal of the storage layer becomes easy. In this case, after writing, magnetic stability (retention) of the storage layer is deteriorated.

As can be seen, reduction of a write current necessary for the magnetic reversal of the storage layer and magnetic stability of the storage layer after writing have a trade-off relationship.

BRIEF DESCRIPTION OF THE DRAWINGS

FIGS. **1**A and **1**B are cross-sectional views showing magnetoresistive elements according to embodiments;

FIG. **2** is a diagram showing magnetization stabilizing effect;

FIG. **3** is a diagram showing an example of "1"-write operation;

FIG. **4** is a diagram showing an example of "0"-write operation;

FIGS. **5**A and **5**B are diagrams showing a first example of a method of manufacturing the magnetoresistive element;

FIGS. **6**A and **6**B are diagrams showing a second example of a method of manufacturing the magnetoresistive element;

FIG. **7** is a cross-sectional view showing a memory cell as an example of application;

FIGS. **8** and **9** are cross-sectional views showing modifications of region X of FIG. **7**;

FIG. **10** is a cross-sectional view showing a first example of a magnetoresistive element of FIG. **7**;

FIG. **11** is a cross-sectional view showing a second example of the magnetoresistive element of FIG. **7**;

FIG. **12** is a plan view showing an example of a memory cell array;

FIG. **13** is a cross-sectional view taken along line XIII-XIII of FIG. **12**;

FIG. **14** is a cross-sectional view taken along line XIV-XIV of FIG. **12**;

FIG. **15** is a cross-sectional view taken along line XV-XV of FIG. **12**;

FIG. **16** is a circuit diagram showing an equivalent circuit of the memory cell array area of FIGS. **12** to **15**; and

FIG. **17** is a block diagram showing an example of a memory system in a processor.

DETAILED DESCRIPTION

In general, according to one embodiment, a magnetoresistive element comprises: a first magnetic layer as a reference layer; a second magnetic layer as a storage layer; a nonmagnetic insulating layer between the first and second magnetic layers; and an antiferromagnetic conductive layer which is adjacent to a side opposite to the nonmagnetic insulating layer side of the second magnetic layer in a vertical direction in which the first and second magnetic layers are stacked. The second magnetic layer includes an area which is magnetically coupled with the antiferromagnetic conductive layer and which has a magnetization direction parallel with a magnetization direction of the second magnetic layer.

1. Magnetoresistive Element

(1) Structure

Each of FIGS. **1**A and **1**B shows an embodiment of a magnetoresistive element.

The embodiment is characterized in that in a magnetoresistive element which comprises a first magnetic layer (a reference layer) **11** having invariable magnetization, a second magnetic layer (a storage layer) **12** having variable magnetization, and a nonmagnetic insulating layer (a tunnel barrier layer) **13** provided therebetween, the magnetization of the second magnetic layer **12** after writing is stabilized by adding an antiferromagnetic conductive layer **14** which is magnetically coupled with the second magnetic layer **12** by exchange coupling.

Here, the invariable magnetization means that the magnetization direction does not change before and after writing, and the variable magnetization means that the magnetization direction may be changed to an opposite direction before and after the writing.

Further, the writing means spin-transfer writing which applies a spin torque to the magnetization of the second magnetic layer **12** by passing a write current (spin-polarized electrons) to the magnetoresistive element.

In this embodiment, it should be noted that which of the first magnetic layer **11** and the second magnetic layer **12** should come at the top is not particularly limited. That is, the second magnetic layer **12** may be provided above the first magnetic layer **11**, or the first magnetic layer **11** may be provided above the second magnetic layer **12**.

Also, in the present embodiment, the so-called perpendicular magnetization type magnetoresistive element is given as an example. However, alternatively, the so-called in-plane magnetization type magnetoresistive element may be adopted.

Each of FIGS. **1**A and **1**B is a drawing which schematically shows the magnetoresistive element, and the size of each constituent element of the magnetoresistive element differs from the actual size.

The magnetoresistive element of FIG. **1**A comprises the first magnetic layer **11** having invariable magnetization, the second magnetic layer **12** having variable magnetization, and the nonmagnetic insulating layer **13** provided therebetween.

A magnetization direction of remanent magnetization of the first magnetic layer **11** is a direction in which the first and the second magnetic layers **11** and **12** are stacked (i.e., a vertical direction). In this embodiment, the remanent magnetization of the first magnetic layer **11** is directed toward the nonmagnetic insulating layer **13**. However, alternatively, it may be directed away from the nonmagnetic insulating layer **13**.

The nonmagnetic insulating layer **13** serves as a tunnel barrier layer. Accordingly, the thickness of the nonmagnetic insulating layer **13** in the vertical direction should preferably be several nanometers or less, for example, 1 nm or so.

The antiferromagnetic conductive layer **14** is disposed on a side of the second magnetic layer **12**, which is opposite the nonmagnetic insulating layer **13**. Also, the second magnetic layer **12** includes an area A which is magnetically coupled with the antiferromagnetic conductive layer **14** by exchange coupling, and has a magnetization direction parallel with a magnetization direction of the second magnetic layer **12**.

In the present embodiment, since magnetization directions of the first and the second magnetic layers **11** and **12** are the vertical direction, a magnetization direction of the area A is also the vertical direction.

In this embodiment, the area A is subjected to exchange coupling in the magnetization direction which is opposite to the magnetization direction of the first magnetic layer **11**. However, alternatively, the area A may be subjected to exchange coupling in a magnetization direction which is the same as the magnetization direction of the first magnetic layer **11**.

The area A has the function of keeping a magnetization direction of remanent magnetization of the second magnetic layer **12** in the vertical direction. That is, the area A has the advantage of improving the magnetic stability (retention) of the second magnetic layer **12** after writing by the exchange coupling between the second magnetic layer **12** and the antiferromagnetic conductive layer **14**.

However, since the antiferromagnetic conductive layer **14** fixes the magnetization of a part of (only the area A of) the second magnetic layer **12**, the remaining portion of the second magnetic layer **12** serves as the storage layer having variable magnetization.

Accordingly, the thickness of the antiferromagnetic conductive layer **14** in the vertical direction is set to an appropriate value in accordance with, for example, materials of the second magnetic layer **12** and the antiferromagnetic conductive layer **14**, such that only the magnetization within the area A of the second magnetic layer **12** is fixed.

Meanwhile, a thermal stability index (Δ value) is used as an index representing the magnetic stability. The Δ value is the ratio of the magnetic anisotropy energy E**1** to the thermal energy E**2** of the second magnetic layer (the storage layer) **12** (E**1**/E**2**), and the greater the Δ value is, the more the magnetization of the second magnetic layer **12** is stabilized.

Recently, by miniaturization of the magnetoresistive element, the volume of the second magnetic layer **12** tends to be reduced, and this means that the magnetic anisotropy energy of the second magnetic layer **12** tends to be reduced. This tendency is desirable for reducing the write current, but is not desirable in terms of the magnetic stability of the second magnetic layer **12**.

Hence, a new technology of improving the magnetic stability of the second magnetic layer **12** is desired. However, in terms of the material of the second magnetic layer **12**, a solution which can be conceived of is only increasing the magnetic anisotropy energy, that is, for example, increasing the anisotropic magnetic field and saturation magnetization.

However, the above solution means increasing the write current, and thus after all, the solution does not improve the situation of a trade-off between reduction of the write current necessary for the magnetic reversal of the second magnetic layer **12** and magnetic stability of the second magnetic layer **12** after writing.

In contrast, if the technology of partially fixing the magnetization of the second magnetic layer **12** by the antiferromagnetic conductive layer **14** (i.e., causing the second magnetic layer **12** to be coupled with the antiferromagnetic conductive layer **14** by exchange coupling) is adopted, as described above, the Δ value can be increased without increasing the anisotropic magnetic field or the saturation magnetization of the second magnetic layer **12**.

Accordingly, for example, in terms of the material of the second magnetic layer **12**, the write current is reduced by reducing the anisotropic magnetic field and the saturation magnetization. Together with that, in terms of the exchange coupling between the second magnetic layer **12** and the antiferromagnetic conductive layer **14**, the Δ value can be increased. Consequently, the situation of a trade-off between reduction of the write current necessary for the magnetic reversal of the second magnetic layer **12** and magnetic stability of the second magnetic layer **12** after writing can be improved.

Note that the materials of the second magnetic layer **12** and the antiferromagnetic conductive layer **14**, thicknesses of these layers, and a crystal structure/orientation, etc., should preferably be controlled such that the exchange coupling between the second magnetic layer **12** and the antiferromagnetic conductive layer **14** exhibits uniaxial anisotropy, not unidirectional anisotropy.

Further, in FIG. **1**A, when the area A has a magnetization direction opposite to the magnetization direction of the first magnetic layer **11**, the area A also has the advantage of cancelling a shift of a magnetization reversal characteristic of the second magnetic layer **12**.

That is, the area A produces a second stray magnetic field which is opposite to a first stray magnetic field caused by the first magnetic layer **11**. Accordingly, since the first and the second stray magnetic fields cancel each other out, it is possible to cancel the shift of the magnetization reversal characteristic of the second magnetic layer **12**.

A magnetoresistive element shown in FIG. **1**B is a modification of the magnetoresistive element of FIG. **1**A.

As compared to the magnetoresistive element of FIG. **1**A, the magnetoresistive element of FIG. **1**B is characterized in that a nonmagnetic conductive layer **10** is further disposed between the second magnetic layer **12** having variable magnetization and the antiferromagnetic conductive layer **14**. Since the other parts of the magnetoresistive element of FIG. **1**B are the same as those of FIG. **1**A, explanation of the same parts will not be provided here.

The nonmagnetic conductive layer **10** has the function of adjusting a range of the exchange coupling between the second magnetic layer (the storage layer) **12** and the antiferromagnetic conductive layer **14**, that is, a width of the area A in the vertical direction. For example, as described above, the second magnetic layer **12** needs to be made to function as a storage layer in which the magnetization of a part near the antiferromagnetic conductive layer **14** (only the area A) is fixed, and the remaining portion of the second magnetic layer **12** has variable magnetization.

However, if the thickness of the second magnetic layer **12** in the vertical direction is reduced, causing the second magnetic layer **12** to function as such becomes difficult, and it is possible that the magnetization of the entire portion of the second magnetic layer **12** will be fixed as a consequence.

In order to avoid such an event, further providing the nonmagnetic conductive layer **10** between the second magnetic layer **12** and the antiferromagnetic conductive layer **14** is an effective measure.

Also, the material of the nonmagnetic conductive layer **10** should preferably be one which can favorably exchange-couple the second magnetic layer **12** and the antiferromagnetic conductive layer **14** with uniaxial anisotropy, not unidirectional anisotropy. The nonmagnetic conductive layer **10** can be selected from the group consisting of Ta, W, Ti, Nb, Hf, Al, and B, for example.

Meanwhile, in order to increase the magnetoresistive (MR) ratio of the magnetoresistive element of FIGS. **1**A and **1**B, when the first and the second magnetic layers **11** and **12** contain CoFeB, the nonmagnetic insulating layer **13** should preferably comprise a material having the NaCL structure which is (001) oriented in the vertical direction, such as MgO.

On the other hand, the antiferromagnetic conductive layer **14** for stabilizing the remanent magnetization of the second magnetic layer **12** is disposed on a side of the second magnetic layer **12**, which is opposite the nonmagnetic insulating layer **13**. Accordingly, the antiferromagnetic conductive layer **14** does not affect the MR ratio of the magnetoresistive element.

For this reason, the antiferromagnetic conductive layer **14** can be arbitrarily selected from any of conductive layers having antiferromagnetic properties without having the limitations of a crystal orientation, a crystal structure, etc.

For example, for the antiferromagnetic conductive layer **14**, PtMn, PdMn, IrMn, RhMn, RuMn, NiMn, FeMn, CoMn, CrMn, etc., can be used.

(2) Magnetization Stabilizing Effect

FIG. **2** shows the magnetization stabilizing effect according to the embodiment described above.

In this figure, a comparative example has the same structure as that of the embodiment, but in this case, magnetic stability using the antiferromagnetic conductive layer is not performed. For example, in the case of FIG. **1**A, the embodiment has the structure of FIG. **1**A as it is, but the comparative example has the structure in which the antiferromagnetic conductive layer **14** of FIG. **1**A is omitted.

Also, a hysteresis curve of this figure shows the degree of easiness/difficulty (disturbs) of the magnetic reversal of the storage layer by an external magnetic field after writing when it is supposed that a value of the write current (a switching current) for the magnetic reversal of the second magnetic layer (the storage layer) is the same in the embodiment and the comparative example.

The horizontal axis of a graph showing the hysteresis curve of FIG. **2** represents the magnitude of the external magnetic field, and the vertical axis represents the intensity of the remanent magnetization of the second magnetic layer (the storage layer).

As is clear from this figure, by adding the antiferromagnetic conductive layer to the magnetoresistive element, magnetization of the second magnetic layer (the storage layer) is hard to be reversed by external disturbance. That is, in the present embodiment, the magnetization of the second magnetic layer (the storage layer) after writing does not reverse unless a large external magnetic field is applied. In contrast, in the comparative example, the magnetization of the second magnetic layer (the storage layer) after writing is easily reversed by a small external magnetic field.

(3) Write Operation

In the magnetoresistive element of the embodiment described above, a write operation is performed by passing a write current (spin-polarized electrons) to the magnetoresistive element. By taking the structure of FIG. **1**A as an example, the write operation will be hereinafter described.

Here, the state in which the magnetization directions of the first and the second magnetic layers **11** and **12** are the same is defined as the parallel state ("0" state) P, and the state in which the magnetization directions of the first and the second magnetic layers **11** and **12** are opposite is defined as the antiparallel state ("1" state) AP. Further, it is assumed that the resistance of the magnetoresistive element in the parallel state P is lower than the resistance of the magnetoresistive element in the antiparallel state AP.

With reference to FIG. **3**, a write operation of changing the state of a magnetoresistive element from the parallel state P to the antiparallel state AP will be described.

For example, when the second magnetic layer **12** is set at 0v, and the first magnetic layer **11** is set to have a positive potential V1, a write current flows from the first magnetic layer **11** to the second magnetic layer **12**. At this time, electrons e^- flow from the second magnetic layer **12** to the first magnetic layer **11**.

Of the electrons flowing from the second magnetic layer **12** to the first magnetic layer **11**, majority-spin electrons in the second magnetic layer **12**, that is, the (upward) electrons which have been spin-polarized in the same direction as the magnetization direction (i.e., the upward magnetization) of the first magnetic layer **11**, are stored in the first magnetic layer **11**. Further, of the electrons flowing from the second magnetic layer **12** to the first magnetic layer **11**, minority-spin electrons in the second magnetic layer **12**, that is, the (downward) electrons which have been spin-polarized in a direction opposite to the magnetization direction (i.e., the upward magnetization) of the first magnetic layer **11**, are returned to the second magnetic layer **12**, and a spin torque is applied to the magnetization in the second magnetic layer **12**. Accordingly, the magnetization direction of the second magnetic layer **12** is changed to the same direction as the magnetization direction of the first magnetic layer **11** (i.e., the state being changed to the antiparallel state).

With reference to FIG. **4**, a write operation of changing the state of the magnetoresistive element from the antiparallel state AP to the parallel state P will be described.

For example, when the second magnetic layer **12** is set to have a positive potential V2, and the first magnetic layer **11** is set at 0v, a write current flows from the second magnetic layer **12** to the first magnetic layer **11**. At this time, electrons e^- flow from the first magnetic layer **11** to the second magnetic layer **12**.

Of the electrons flowing from the first magnetic layer **11** to the second magnetic layer **12**, minority-spin electrons in the second magnetic layer **12**, that is, the (upward) electrons which have been spin-polarized in the same direction as the magnetization direction (i.e., the upward magnetization) of the first magnetic layer **11**, are stored in the second magnetic layer **12**, and a spin torque is applied to the magnetization in the second magnetic layer **12**. Accordingly, the magnetization direction of the second magnetic layer **12** is changed to the same direction as the magnetization direction of the first magnetic layer **11** (i.e., the state being changed to the parallel state).

(4) Manufacturing Method

An example of a method of manufacturing the magnetoresistive element of the above embodiment will be described.

The manufacturing method has the feature in the way in which the second magnetic layer and the antiferromagnetic conductive layer are exchange-coupled. By taking the structure of FIG. **1**A as an example, the manufacturing method will be hereinafter described.

First Example

FIGS. **5**A and **5**B show a first example of the manufacturing method.

Firstly, as shown in FIG. **5**A, a magnetoresistive element comprising the first magnetic layer **11**, the second magnetic layer **12**, the nonmagnetic insulating layer **13**, and the antiferromagnetic conductive layer **14** is formed.

After that, in a state where external magnetic field Hext_**1** in a first (downward) direction is applied, by changing a temperature from a value greater than blocking temperature Tb determined by the second magnetic layer **12** and the antiferromagnetic conductive layer **14** to a value less than blocking temperature Tb, the second magnetic layer **12** and the antiferromagnetic conductive layer **14** are magnetically coupled by exchange coupling, and an area A in which the magnetization direction conforms to the first direction is formed in the second magnetic layer **12**.

Next, as shown in FIG. **5**B, after forming the area A in the second magnetic layer **12**, by applying external magnetic field Hext_**2** in a second (upward) direction which is opposite to the first (downward) direction, the magnetization direction of the second magnetic layer **12** is steered to the second direction.

Second Example

FIGS. **6**A and **6**B show a second example of the manufacturing method.

Firstly, as shown in FIG. **6**A, a magnetoresistive element comprising the first magnetic layer **11**, the second magnetic layer **12**, the nonmagnetic insulating layer **13**, and the antiferromagnetic conductive layer **14** is formed.

After that, by applying external magnetic field Hext_**1** in a first (upward) direction, the magnetization direction of the first magnetic layer is made to conform to the first direction.

Next, as shown in FIG. **6**B, after steering the magnetization direction of the first magnetic layer **11** to the first direction, in a state where external magnetic field Hext_**2** in a second (downward) direction, which is opposite to the first (upward) direction, is applied, by changing a temperature from a value greater than blocking temperature Tb determined by the second magnetic layer **12** and the antiferromagnetic conductive layer **14** to a value less than blocking temperature Tb, the second magnetic layer **12** and the antiferromagnetic conductive layer **14** are magnetically coupled by exchange coupling, and an area A in which the magnetization direction conforms to the second direction is formed in the second magnetic layer **12**.

Blocking Temperature

Blocking temperature Tb at which the second magnetic layer **12** and the antiferromagnetic conductive layer **14** are exchange-coupled differs for each material which constitutes the aforementioned layers.

For example, when the second magnetic layer **12** is made of CoFeB, blocking temperature Tb varies according to the material of the antiferromagnetic conductive layer **14** as described below.

For example, Tb of NiMn of the fct structure is approximately 380°, Tb of PtMn of the fct structure is approximately 350°, Tb of IrMn of the fct structure is approximately 300°, Tb of CrMn of the bct structure is approximately 250°, Tb of PdMn of the fct structure is approximately 250°, and Tb of FeMn of the fcc structure is approximately 150°.

(5) Example of Material

Referring to FIGS. **1**A and **1**B, the first magnetic layer **11** and the second magnetic layer **12** include a magnetic material of any of Co, Fe, Ni, and Mn. Also, the first and the second magnetic layers **11** and **12** may include oxygen (O). In this case, the amount of oxygen may be varied in the first and the second magnetic layers **11** and **12**.

The first and the second magnetic layers **11** and **12** may comprise, for example, CoFeB, MgFeO, and a lamination of these materials.

In the case of a magnetoresistive element having perpendicular magnetization, the first and the second magnetic layers **11** and **12** should preferably comprise TbCoFe having perpendicular magnetic anisotropy, an artificial lattice in which Co and Pt are stacked, L1o-ordered FePt, etc.

2. Application Example

FIG. **7** shows an example of a memory cell of a magnetic memory.

In this example, the memory cell of the magnetic memory comprises a select transistor (for example, an FET) ST and a magnetoresistive element MTJ. The magnetoresistive element MTJ is a magnetoresistive element of the above embodiment.

The select transistor ST is arranged within an active area AA in a semiconductor substrate **21**. The active area AA is surrounded by an element isolation insulating layer **22** in the semiconductor substrate **21**. In this example, the element isolation insulating layer **22** has a shallow trench isolation (STI) structure.

The select transistor ST comprises source/drain diffusion layers **23***a* and **23***b* in the semiconductor substrate **21**, a gate insulating layer **24** on a channel between these source/drain diffusion layers **23***a* and **23***b*, and a gate electrode **25** on the gate insulating layer **24**. The gate electrode **25** serves as a word line.

An interlayer insulating layer (for example, a silicon oxide layer) **26** covers the select transistor ST. Contact plugs BEC and BC**1** are arranged within the interlayer insulating layer **26**. An upper surface of the interlayer insulating layer **26** is flat, and a bottom electrode (a first electrode) **15** is arranged on the interlayer insulating layer **26**.

The bottom electrode **15** comprises, for example, one of Al, Be, Mg, Ca, Sr, Ba, Sc, Y, La, Zr, and Hf, an alloy including one of the aforementioned elements, or a compound of one of the aforementioned elements or the alloy and B (for example, HfB, MgAlB, HfAlB, ScAlB, ScHfB, HfMgB, etc.).

The bottom electrode **15** is connected to the source/drain diffusion layer **23***a* of the select transistor ST via contact plug (bottom electrode contact) BEC. Contact plug BC**1** is connected to the source/drain diffusion layer **23***b* of the select transistor ST.

An under layer **16** is disposed on the bottom electrode **15**. The under layer **16** is provided to crystallize the magnetoresistive element MTJ. The under layer **16** should preferably contain, for example, MgO or a nitrogen compound such as AlN, MgN, ZrN, NbN, SiN, and AlTiN.

The magnetoresistive element MTJ is disposed on the under layer **16**. The cap layer **19** is disposed on the magnetoresistive element MTJ. The cap layer **19** serves as a buffer layer which prevents a reaction between the magnetoresistive element MTJ and a top electrode **20**. The cap layer **19** comprises, for example, Pt, W, Ta, and Ru.

The top electrode **20** is disposed on the cap layer **19**. The top electrode **20** comprises, for example, W, Ta, Ru, Ti, TaN, and TiN.

The top electrode **20** does not only serve as an electrode, but also serves as a mask when patterning the magnetoresistive element MTJ. That is, the top electrode **20** should preferably have low electrical resistance, and comprise a material having good resistance to diffusion, etching, milling, etc., which is, for example, a lamination of Ta/Ru.

A protection insulating layer (for example, a silicon nitride layer) PL covers a side wall of the magnetoresistive element MTJ. An interlayer insulating layer (for example, a silicon oxide layer) **27** is disposed on the protection insulating layer PL, and covers the magnetoresistive element MTJ. An upper surface of the interlayer insulating layer **27** is flat, and bit lines BL**1** and BL**2** are arranged on the interlayer insulating layer **27**.

Bit line BL**1** is connected to the top electrode **20** via contact plug (top electrode contact) TEC. Bit line BL**2** is connected to contact plug BC**1** via contact plug BC**2**.

In this example, the magnetoresistive element MTJ is larger than contact plug BEC in a direction parallel to a surface of the semiconductor substrate **21** (i.e., an in-plane direction).

However, the size is not limited to the above example, and as shown in FIG. **8**, for example, the magnetoresistive element MTJ may have the same size as contact plug BEC in the direction parallel to the surface of the semiconductor substrate **21**. Also, as shown in FIG. **9**, the magnetoresistive element MTJ may be smaller than contact plug BEC in a direction parallel to the surface of the semiconductor substrate **21**.

Here, region X in FIGS. **8** and **9** corresponds to region X of FIG. **7**.

FIGS. **10** and **11** show examples of the magnetoresistive element shown in FIGS. **7** to **9**.

The magnetoresistive element MTJ of FIG. **10** is an example of applying the magnetoresistive element of FIG. **1**A to the memory cell of the magnetic memory of FIGS. **7** to **9** as a top-pin type magnetoresistive element.

In this example, the antiferromagnetic conductive layer **14** is disposed on the under layer **16**, the second magnetic layer (the storage layer) **12** is disposed on the antiferromagnetic conductive layer **14**, the nonmagnetic insulating layer **13** is disposed on the second magnetic layer **12**, and the first magnetic layer (the reference layer) **11** is disposed on the nonmagnetic insulating layer **13**.

Further, a third magnetic layer (a shift cancellation layer) **18** is disposed over the first magnetic layer **11** with a nonmagnetic conductive layer **17** interposed therebetween. The third magnetic layer **18** has a magnetization direction opposite to the magnetization direction of the first magnetic layer **11**, and has the function of cancelling a shift of the magnetization reversal characteristic of the second magnetic layer **12**.

That is, the third magnetic layer **18** produces a second stray magnetic field which is opposite to a first stray magnetic field caused by the first magnetic layer **11**. Since the first and the second stray magnetic fields cancel each other out, it is possible to cancel the shift of the magnetic reversal characteristic of the second magnetic layer **12**.

The cap layer **19** is disposed on the third magnetic layer **18**.

Since the other parts are the same as those of the memory cell of the magnetic memory of FIGS. **7** to **9**, the same reference numbers are assigned to elements which are the same as those of FIGS. **7** to **9**, and explanation of them is omitted.

The magnetoresistive element MTJ of FIG. **11** is an example of applying the magnetoresistive element of FIG. **1**A to the memory cell of the magnetic memory of FIGS. **7** to **9** as a bottom-pin type magnetoresistive element.

In this example, the third magnetic layer (the shift cancellation layer) **18** is disposed on the under layer **16**, the nonmagnetic conductive layer **17** is disposed on the third magnetic layer **18**, the first magnetic layer (the reference layer) **11** is disposed on the nonmagnetic conductive layer **17**, and the nonmagnetic insulating layer **13** is disposed on the first magnetic layer **11**. Further, the second magnetic layer (the storage layer) **12** is disposed on the nonmagnetic insulating layer **13**, and the antiferromagnetic conductive layer **14** is disposed on the second magnetic layer **12**.

The cap layer **19** is disposed on the antiferromagnetic conductive layer **14**.

As in the structure of FIG. **10**, the third magnetic layer **18** has the magnetization direction opposite to the magnetization direction of the first magnetic layer **11**, and also has the function of cancelling a shift of the magnetization reversal characteristic of the second magnetic layer **12**.

Since the other parts are the same as those of the memory cell of the magnetic memory of FIGS. **7** to **9**, the same reference numbers are assigned to elements which are the same as those of FIGS. **7** to **9**, and explanation of them is omitted.

FIGS. **12** to **16** show an example of a memory cell array area of a magnetic random-access memory. FIG. **12** is a plan view of the memory cell array area, FIG. **13** is a cross-sectional view taken along line XIII-XIII of FIG. **12**, FIG. **14** is a cross-sectional view taken along line XIV-XIV of FIG. **12**, and FIG. **15** is a cross-sectional view taken along line XV-XV of FIG. **12**. FIG. **16** shows an equivalent circuit of the memory cell array area of FIGS. **12** to **15**.

In FIGS. **12** to **15**, the same reference numbers are assigned to elements which are the same as those of FIGS. **7** to **11**.

In this example, the so-called two-transistor-one-element-type memory cell, in which a single memory cell MC within a memory cell array area MA includes two select transistors ST and one magnetoresistive element MTJ, will be described. However, this does not mean that the embodiment described above is applied to only this type. That is, the above embodiment can be applied to other types of memory cells in the memory cell array area MA, such as a one-transistor-one-element-type memory cell and a cross-point-type memory cell.

On the semiconductor substrate **21**, memory cells MC are arranged as an array. The memory cell MC comprises two select transistors ST on the semiconductor substrate **21**, and one magnetoresistive element MTJ which is connected to the two select transistors ST in common.

Each of the select transistors ST comprises the source/drain diffusion layers **23***a* and **23***b* in the semiconductor substrate **21**, and a word line WL as a gate electrode on a channel between the source/drain diffusion layers **23***a* and **23***b*. The word line WL extends in a second direction, and is connected to a word line driver **31**.

The magnetoresistive element MTJ is disposed above the source/drain diffusion layer **23***a*, and is connected to the source/drain diffusion layer **23***a*. Also, bit line BL**1** is disposed above the magnetoresistive element MTJ, and is connected to the magnetoresistive element MTJ. Bit line BL**1** extends in a first direction, and is connected to a bit line driver/sinker **32**.

Bit line BL**2** is disposed above the source/drain diffusion layer **23***b*, and is connected to the source/drain diffusion layer **23***b*. Bit line BL**2** also serves as a source line SL which is connected to, for example, a sense amplifier, at the time of a read operation. Bit line BL**2** extends in the first direction, and is connected to a bit line driver/sinker & read circuit **33**.

The layout of the memory cell array area of the example is only exemplification, and it may be changed as needed. For example, in this example, when the memory cell array area MA is seen from above the semiconductor substrate **21**, a mutual positional relationship among the source/drain diffusion layers **23***a* and **23***b*, the magnetoresistive element MTJ, and bit line BL**1** is shifted in the second direction. However, whether the aforementioned constituent elements are shifted, and the shift amount can be changed as appropriate.

Also, in this example, while bit lines BL**1** and BL**2** are formed in different interconnect layers, they may be formed in the same interconnect layer.

FIG. **17** shows an example of a memory system in a processor.

A CPU **41** controls an SRAM **42**, a DRAM **43**, a flash memory **44**, a ROM **45**, and a magnetic random-access memory (MRAM) **46**.

The embodiment described above is applied to the memory cell (the magnetoresistive element) within the MRAM **46**.

The MRAM **46** can be used as a substitute for any of the SRAM **42**, the DRAM **43**, the flash memory **44**, and the ROM **45**. Accordingly, at least one of the SRAM **42**, the DRAM **43**, the flash memory **44**, and the ROM **45** may be omitted.

The MRAM **46** can be used as a nonvolatile cache (for example, an L2 cache).

3. Conclusion

As described above, according to the present embodiment, it is possible to improve the situation of a trade-off between reduction of a write current necessary for the magnetic reversal of the storage layer and magnetic stability of the storage layer after writing.

While certain embodiments have been described, these embodiments have been presented by way of example only, and are not intended to limit the scope of the inventions. Indeed, the novel embodiments described herein may be embodied in a variety of other forms; furthermore, various omissions, substitutions and changes in the form of the embodiments described herein may be made without departing from the spirit of the inventions. The accompanying claims and their equivalents are intended to cover such forms or modifications as would fall within the scope and spirit of the inventions.

What is claimed is:

1. A magnetoresistive element comprising:

a first magnetic layer as a reference layer;

a second magnetic layer as a storage layer;

a nonmagnetic insulating layer between the first and second magnetic layers; and

an antiferromagnetic conductive layer which is adjacent to a side opposite to a nonmagnetic insulating layer side of the second magnetic layer in a vertical direction in which the first and second magnetic layers are stacked,

wherein the second magnetic layer includes an area which is magnetically coupled with the antiferromagnetic conductive layer and which has a magnetization direction parallel with a magnetization direction of the second magnetic layer.

2. The element of claim **1**, wherein each of the first and second magnetic layers has remanent magnetization in the vertical direction, and the area has the magnetization direction in the vertical direction.

3. The element of claim **1**, wherein the area has the magnetization direction opposite to a magnetization direction of the first magnetic layer.

4. The element of claim **1**, further comprising:

a nonmagnetic conductive layer between the second magnetic layer and the antiferromagnetic conductive layer.

5. The element of claim **1**, wherein the antiferromagnetic conductive layer comprises one of PtMn, PdMn, IrMn, RhMn, RuMn, NiMn, FeMn, CoMn, and CrMn.

6. The element of claim **1**, further comprising:

a third magnetic layer having a magnetization direction opposite to a magnetization direction of the first magnetic layer.

7. The element of claim **6**, further comprising:

a nonmagnetic conductive layer between the first magnetic layer and the third magnetic layer.

8. The element of claim **1**, wherein the magnetization direction of the second magnetic layer is changed by a write current which flows between the first and second magnetic layers.

9. A magnetoresistive element comprising:

a first magnetic layer as a reference layer;

a second magnetic layer as a storage layer;

a nonmagnetic insulating layer between the first and second magnetic layers; and

a conductive layer which is adjacent to a side opposite to a nonmagnetic insulating layer side of the second magnetic layer in a vertical direction in which the first and second magnetic layers are stacked,

wherein the conductive layer comprises one of PtMn, PdMn, IrMn, RhMn, RuMn, NiMn, FeMn, CoMn, and CrMn.

10. The element of claim **9**, wherein the second magnetic layer includes an area which is magnetically coupled with the conductive layer and which has a magnetization direction parallel with a magnetization direction of the second magnetic layer.

11. The element of claim **10**, wherein each of the first and second magnetic layers has remanent magnetization in the vertical direction, and the area has a magnetization direction in the vertical direction.

12. The element of claim **10**, wherein the area has the magnetization direction opposite to a magnetization direction of the first magnetic layer.

13. The element of claim **9**, further comprising:

a nonmagnetic conductive layer between the second magnetic layer and the conductive layer.

14. The element of claim **9**, further comprising:

a third magnetic layer having a magnetization direction opposite to a magnetization direction of the first magnetic layer.

15. The element of claim **14**, further comprising:

a nonmagnetic conductive layer between the first magnetic layer and the third magnetic layer.

16. The element of claim **9**, wherein a magnetization direction of the second magnetic layer is changed by a write current which flows between the first and second magnetic layers.

17. The element of claim **1**, wherein the magnetization direction of the area of the second magnetic layer is parallel with the magnetization direction of the second magnetic layer after a write operation.

18. The element of claim **9**, wherein a magnetization direction of an area of the second magnetic layer is parallel with a magnetization direction of the second magnetic layer after a write operation.

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